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MAD COW DISEASE. In 1986, Bovine Spongiform Encephalopathy (BSE) was described in the United Kingdom and dubbed "Mad Cow Disease" because the infectious agent caused brain tissue to become sponge-like and make the animal "mad." Ten years later, after thousands of cows had been infected and prematurely slaughtered so that they would not enter the human food chain, a new human disease appeared. Fifteen young U.K. residents were diagnosed with a similar brain-wasting condition, variant Creutzfeldt-Jakob disease (vCJD). CJD had been known for some time.

During its first five years of named existence, vCJD had struck ninety-six people in the United Kingdom as of June 2001, and perhaps two or three elsewhere. Ninety percent of the world's 180,900 cases of BSE had occurred in the UK. That prompted the scientific community to conclude that "the most likely way people got vCJD was from eating tainted beef."

BSE aroused scientific and policy debate for some years. In 1996, some warned that the Mad Cow crisis would be the AIDS epidemic the UK never had. In 2000, when the disease migrated to continental Europe, the *Frankfurter Allgemeine* compared it to Europe's Black Death of the fourteenth century.

Mad Cow Disease became a continuing problem not only because of the threat to animal health—a real threat that claimed the lives of thousands of cattle—but also because of the scientific uncertainty of the length of incubation, the presence of the infective agent, and the actual vector of transmission. Scientists still do not know how people get vCJD in the first place. A recent report of the House of Lords again pointed to eating beef as the most probable assumption.

United Nations agencies responded to the challenge through the Office of International Epizootes (OIE), the Food and Agriculture Organization (FAO), and the World Health Organization (WHO), which created policies to eliminate the threat to animal and human health. Since the consensus held that the disease originated from feeding infectious animal products to cattle, the practice was stopped, surveillance implemented, and certain beef and beef products banned.

The infectious agent responsible for the disease could be a self-replicating protein called a prion. Or, what many believe more likely, it could be viral-like, with nucleic acids carrying genetic information. The agent cannot be identified easily in live animals or humans since it resides mainly in the central nervous system. Science has hedged its bets about the risk of BSE to humans: "theoretical," "hypothetical," "negligible," "remote," and "incalculably small" were the terms used to describe the risk to humans. But the loss to agriculture, trade, and other industries has been almost incalculably large, some $20 billion according to recent estimates. Some believe the response has extended well beyond the threat to human health.

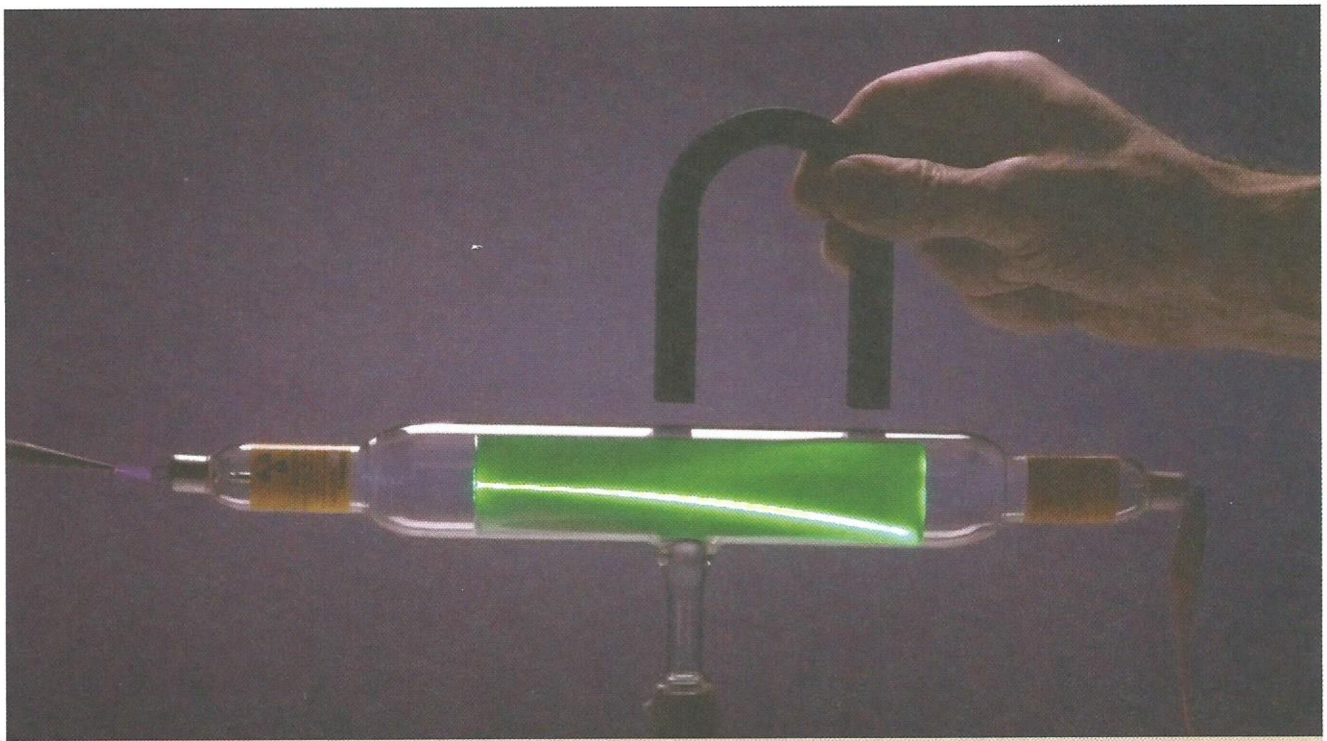
The case of Mad Cow Disease illustrates how modern society blurs facts and fears. Fears generated by the BSE crisis spilled over to genetically modified foods, biomedical research, and other scientific programs. The episode also highlights some of the challenges of globalization. Multilateral organizations and multinational companies provide the resources for protecting public health, but public fear and emotion often impede reason and appropriate policy responses.

Scott C. Ratzan

MAGNETO-OPTICS. The effects of magnetic fields on light have had an importance for physical theory far beyond their significance in nature since their first detection in 1845. That occurred because William Thomson, Lord Kelvin, inferred from Michael Faraday's ideas about electricity and his own ideas about light that glass stressed by an electric field should rotate the plane of polarized light passing through it. Faraday looked, found nothing, and substituted a magnetic field, which worked. Success prompted a characteristic leap; Faraday inferred that magnetism could be concentrated, as it had been in the experiment, by materials other than ferromagnetics. This insight, the first spin-off from a magneto-optical effect, led him to the discoveries of para- and diamagnetism.

In 1862, Faraday sought to change the spectrum of a light source by placing it in a magnetic field. No luck. But the fact that he had tried encouraged a repetition some thirty years later. Pieter Zeeman had just obtained his doctorate from the University of Leyden with a prize-winning thesis on a second magneto-optic effect, the change in polarization of plane-polarized light reflected from an electromagnet. In 1896, Zeeman saw the bright yellow lines of sodium broaden when he placed their source in a magnetic field. He brought this news to his professor, Hendrik Antoon Lorentz. From his own model for the emission of light, in which the radiator is an "ion" of unknown charge e and mass m, Lorentz predicted that the broadened lines should be resolvable into triplets polarized in certain ways and separated by a distance proportional to e/m. Zeeman confirmed the prediction and deduced the value of e/m. It came out close to the number that Joseph John Thomson had found for the ratio of charge to mass of cathode-ray particles. The "Zeeman effect" played a major part in the establishment of the electron as a building block of matter. Zeeman and Lorentz shared the Nobel Prize for physics in 1902.

Most Zeeman patterns differ from Lorentz's triplet. Explaining quartets, quintets, and so on proved too much for both classical and early quantum theories of atomic structure and spectral emission. After World War I, demobilizing physicists found the "anomalous Zeeman effect," which most of them had ignored, high among the outstanding problems of atomic physics as described in Arnold Sommerfeld's comprehensive survey, *Atombau and Spektrallinien* (1919).



A magnet appears to bend light in a cathode ray tube.

Lorentz's theory derived the magnitude of the line splitting from *g*, the ratio of the magnetic moment to the orbital angular momentum of the radiating electron. Alfred Landé, a young Jewish theorist at the University of Frankfurt am Main, managed to refer the refractory splitting to an anomalous value of *g* and to accepted rules for quantum transitions. Attempts to derive the anomalous *g* from an atomic model failed until the introduction of electron spin in 1925 by Samuel Goudsmit and George Uhlenbeck, young Dutch physicists who, like Landé, made their careers in the United States. Meanwhile, analysis of the systematics of quantum transitions in the anomalous effect helped to guide Wolfgang Pauli to the most striking of all the discoveries prompted by magneto-optical phenomena: the "Exclusion Principle," which ascribes four quantum numbers to each electron in an atom and prohibits any two electrons from having the same values for all their quantum numbers. Pauli's fourth quantum number was soon associated with Goudsmit and Uhlenbeck's spin. Particles that, like electrons, are exclusive, divide the universe with particles that, like photons, are gregarious. Both sorts have revealed much when under the influence of a magnetic field.

J. L. HEILBRON

Claude-Louis Berthollet (1748–1822), French doctor and chemist

MASS ACTION. The law of mass action expresses the mathematical relationship between the quantities of the substances present at the beginning of a chemical reaction in which they participate and the quantities of both reactants and products present when the reaction has reached an equilibrium. Although formulated in essentially its present form as an equation during the late nineteenth century, its underlying concept goes back to around 1800 and the French chemist Claude Louis Berthollet.

Eighteenth-century chemists organized much of their cumulative knowledge of the chemical operations they could carry out in their laboratories in the form of tables of "rapports" or "affinities" which they also sometimes called "elective attractions." These tables expressed in highly compressed form the order in which substances would replace each other in combination with a third substance. In the case of interactions or "double decompositions" between two neutral salts, the affinity tables expressed the direction in which this exchange took place. The Swedish chemist Torbern Bergman published the most complete affinity table of the century in 1778. He performed thousands of experiments to gather the information arranged in it. In some cases, the exchange seemed to go in the opposite direction from the expected order. Heating the substances, for example, disrupted the order established by operations carried out in solution at room temperature; but Bergman believed that more careful control and further experimentation would suffice to eliminate these apparent inconsistencies.

Berthollet encountered similar anomalies, some of which referred to the insolubility or volatility of a product, which removed it from the solution. Moreover, the normal direction of a chemical change could often be overcome by adding much greater amounts of one of the products. Berthollet concluded that chemical changes do not go to completion except when one or more of the products is removed; otherwise the proportion between the initial and final products depends on their relative masses as well as their affinities.

Berthollet connected these views with a belief that chemical compounds exist in indefinite proportions in solution. When the acceptance of John Dalton's atomic theory discredited this belief, some of Berthollet's contemporaries inferred that his views on mass action were untenable; others, however, including the influential Jöns Jacob Berzelius, could separate these ideas. For several decades chemists regarded Berthollet's mass action as a competitor to Bergman's affinities. The issue appeared chemically insoluble, because the relative quantities of each substance present in a solution could not be determined without applying reagents that themselves disturbed the equilibrium.

In 1862, Marcellin Berthelot and Péan de Saint-Gilles devised an effective way to test Berthollet's concept of mass action by studying the very slow chemical reaction between an alcohol and an organic acid to form an ester and water. At intervals they removed small portions of the solution and titrated the acid with a base without affecting the reaction sensibly. Their results strongly confirmed Berthollet's mass action and stimulated two Norwegian chemists, Cato Guldberg and Peter Waage, to make similar determinations using particularly sluggish inorganic reactions. Guldberg and Waage obtained results analogous to those of the French team and in 1864 published a mathematical law of mass action, which they subsequently simplified. By 1879, they had arrived at the form of the law that has been used ever since.

FREDERIC LAWRENCE HOLMES

MASS SPECTROGRAPH. The mass spectrograph is an electromagnetic instrument for separating ions on the basis of their charge to mass ratio (*e/m*), and hence for studying their mass and chemical nature. In 1912, Joseph John Thomson and his assistant Francis Aston, analyzing positive rays (ions that stream through a hole in the cathode of a gas-discharge tube), discovered an ion closely associated with that of neon, atomic mass 20, but corresponding to mass 22. For several years identification of this ion as a compound, a new element, or an isotope of neon remained uncertain, but from 1913, Frederick Soddy actively promoted it as evidence of isotopes in nonradioactive substances.

The subsequent development of the mass spectrograph is intimately connected with Soddy's concept of isotopes and the Rutherford-Bohr atom. The first instruments, invented by Arthur Dempster in Chicago in 1918 and Aston in Cambridge in 1919, both attempted to separate isotopes unambiguously using variations on Thomson's positive-ray apparatus. But it was Aston, working in the Cavendish Laboratory at Cambridge under Ernest Rutherford, whose name became linked with the mass spectrograph.

The two instruments relied on different focusing techniques and produced different types of results. In Aston's mass spectrograph perpendicular electric and magnetic fields focused ions with different masses at different points on a photographic plate. Aston identified and measured the atomic weights of a large number of isotopes; established the "whole number rule" for atomic weights (that isotopic masses are integral multiples of that of hydrogen, then known only as a single isotope of mass 1); and, with his second instrument of 1925, measured deviations from this rule, the "packing fraction" of nuclei (a measure of the mass equivalent of the energy binding the constituents of a nucleus together). He received the Nobel Prize for chemistry in 1922 for his work. Mass spectrographs are used extensively for accurate atomic weight determination.

Dempster's instrument, which Aston refused to call a "mass spectrograph" because it provided a momentum rather than mass spectrum, established a tradition of "mass spectrometers." In this design, a magnetic field perpendicular to the plane of a beam of ions causes them to move in a circle whose radius depends on the mass and velocity of the particles. In half a turn around a narrow vacuum chamber, ions of the same mass and velocity can be caught in a cup, the others having ended in the walls of the chamber. Dempster used a quadrant electrometer to detect them in the cup quantitatively. By varying the accelerating potential he selected different ions and measured their relative abundance. Although he failed to distinguish unambiguously between the hypothetical isotopes of magnesium and chlorine, Dempster opened the way for accurate abundance determinations and subsequently discovered many isotopes.

From the mid-1920s on several different types of mass spectrograph have been developed to meet the needs of spectroscopists, atomic-weight chemists, and radioactivists. The most important of these instruments were those of Kenneth Bainbridge (1933), who provided the first experimental proof of the Einstein mass-energy relationship, and Alfred Neir, who introduced a 60-degree (rather than 180-degree) analyzer in 1940. In the 1930s and 1940s physicists invented other electromagnetic means of separating ions: time-of-flight, radio-frequency, and cyclotron-resonance instruments in particular. By this time isotopes had become fundamental to many physical sciences, commercial instruments were available, and the earlier distinction between mass spectrographs and spectrometers had been lost as mass spectrometry became established as a central technique in an era of increasing reliance on instrumentation.

ISOBEL FALCONER

MATERIALS SCIENCE. Although materials have long been objects of scientific inquiry—Galileo discussed the strength of beams in his *Two New Sciences* (1638)—the academic discipline of materials science appeared only recently. The mechanics of elastic bodies, which developed as a kind of mixed science, became an integral part of the program of experimental philosophy developed by Robert Hooke at the Royal Society, by Edmé Mariotte in France, and by Jakob Bernoulli in Switzerland. Only in retrospect, however, can we identify these studies of the mechanical properties of wood or iron as a protoscience of materials. The generic notion of materials is a fairly recent invention. The new discipline emerged around 1960 when the departments of metallurgy of a number of academic institutions were renamed "metallurgy and materials science" and a few years later materials science emerged as an autonomous entity.

This linguistic change reflected an inner evolution of metallurgy toward the determination of crystalline structures.

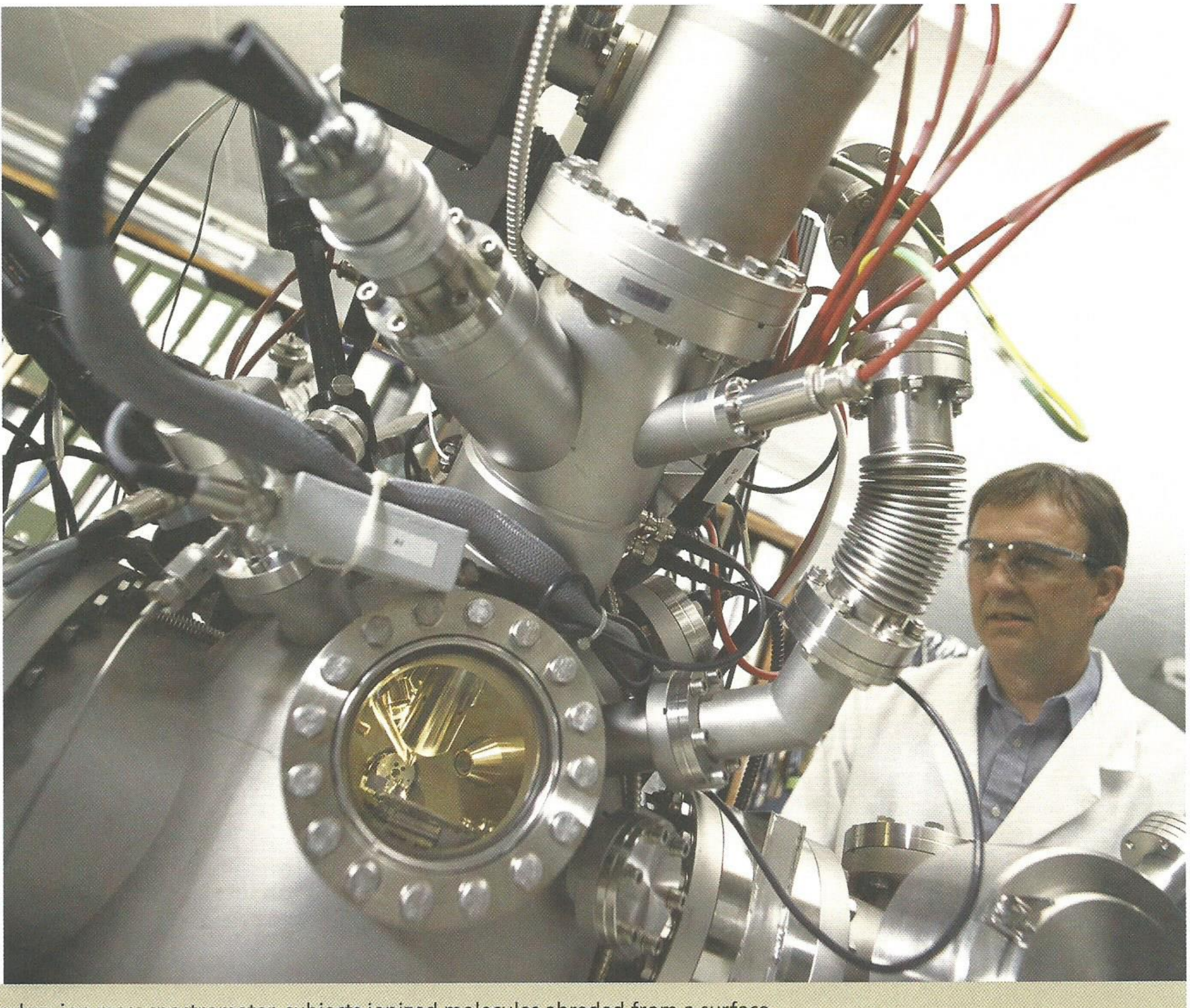
Beginning with the study of crystals by X-ray diffraction (1913), the determination of microstructure became the prime concern of physical metallurgy. The notions of crystal lattices, dislocation, and defect proved key to understanding the macroscopic behavior of metals. The connections between microstructure and mechanical properties were probed, and the models and theories elaborated by physicists put to work for designing new materials.

X-ray diffraction techniques gave precise atomic pictures of solids, and quantum mechanics provided the theoretical foundations for their further description. The solid state became an object of investigation in itself. Solid-state physicists discriminated between properties depending on the idealized crystal pattern and properties dependent on "accidents" of the inner arrangement or of the surface of the solid. This stress on structure-sensitive properties in the study of crystals turned the subject toward materials science.

A solid is not a material, however. The notion of materials combines physical and chemical properties with social needs and industrial or military interests. This hybrid concept implies that knowing and producing cannot be separated. Significantly, the discipline that emerged in the 1960s has been named "materials science and engineering" (MSE).

The generic notion of materials first appeared in the language of policy makers and referred to a bottleneck holding up advances in space and military technologies. The idea that all materials were strategic emerged during the Cold War in the United States in response to *Sputnik*. Designers sought high-performance materials with previously unknown properties for use in extreme circumstances. The Department of Defense's Advanced Research Project Agency (ARPA) invested heavily in academic research on materials and created interdisciplinary laboratories equipped with expensive instruments to prompt joint research involving metallurgists; chemical, electrical, and mechanical engineers; chemists; solid-state physicists; and electronics specialists. This program created the research field of MSE, at this stage mainly an American science. In Europe, a number of materials science centers grew out of former metallurgy departments, but materials did not become a political concern and solid-state chemistry emerged more prominently.

In the 1970s, new social priorities reoriented academic research from military to civilian goals. Environmental and safety legislation, together with economic competition with Japan, put new demands on material scientists. Materials science was now conceived as a response to "man's needs." While the U.S. federal budget for research and development stagnated, industrial companies became more engaged and



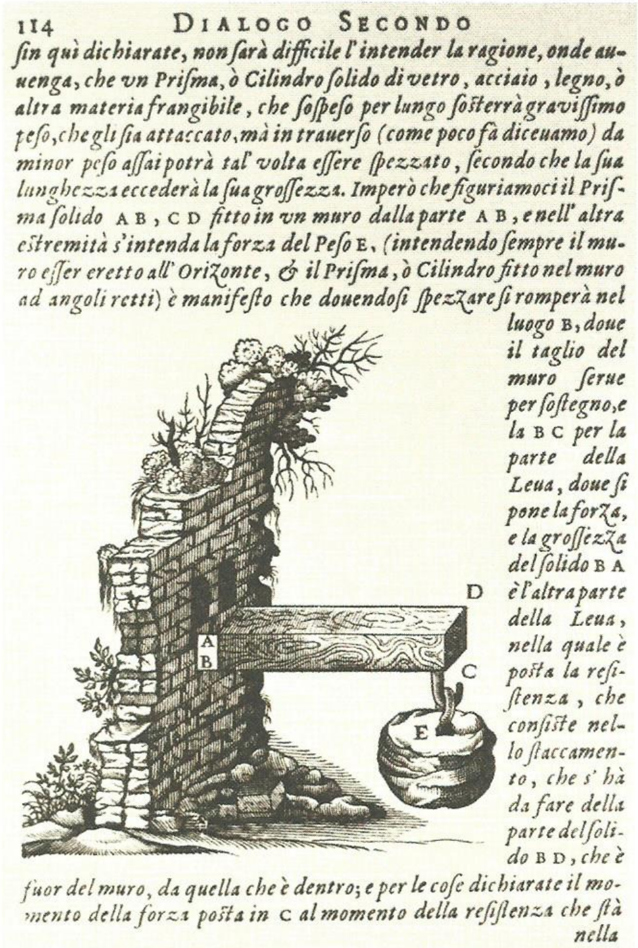
A secondary ion mass spectrometer, subjects ionized molecules abraded from a surface to a time-of-flight measurement, which determines their acceleration and thence their mass.

research became more concerned with process. The interrelation of structures and properties with functions and processes, visually represented by a tetrahedron in many textbooks, provided the conceptual framework for MSE and helped to make it an established, teachable discipline. Courses in MSE proliferated in engineering schools, an annual review of materials science started (1971), and a Materials Research Society (1973) and a European Materials Research Society (1983) appeared.

At the same time the leadership that physicists and metallurgists had exerted passed to chemists. Development of composite materials made of a matrix reinforced with fibers acted as a driving force in the formation of the discipline. Unlike conventional mass-produced plastics, composite materials are shaped to achieve specific functions and respond to specific demands. They offer the paradigm of "materials by design," a product of science and technology working together. Composites technology reinforced thinking in terms of four variables—structure, properties, performance, and processes; changes made in any of them can have a significant effect on the performance of the whole system and require a rethinking of the entire device. The traditional linear approach—given a set of functions find the properties required and design the structure combining them—gave way to a systems approach aided by computer simulation. The synergy between the four composite material variables called for a synergy between various specialists and a new organization of labor in project teams.

In the 1990s, academic research regained dominance. Following a drastic reduction of technical staff at most industrial companies, many industrial researchers joined university laboratories. MSE continued to diversify. Part of the materials science community shifted from microscale to nanoscale analysis. Instruments, which had already played a decisive role in the emergence of MSE with X-ray diffraction in the 1920s and the transmission electron microscope in the 1950s, once again proved crucial: the scanning tunneling microscope and the atomic force microscope allow not only the visualization but also the manipulation of individual atoms. With nanotechnology, materials are no longer carved like a statue out of a block of marble but by bonding atoms or groups of atoms. The key step becomes the assembly of building blocks.

In the 1990s, materials scientists suddenly became interested in mollusk shells, insect cuticles, algae, and spider silk. These composite structures, associating the hard and the soft, combining inorganic and organic components, capable of high performance, appeared as models for human technology in three respects. They are models of functional materials, optimally performing several functions including growth, repair, and recycling. They are models of structure: the remarkable properties of bulk materials such as bone or wood result from a complex arrangement at different levels, each controlling the next; the hierarchy of structures from the molecular to the macroscopic appears as a mark of the superiority of nature's design over human engineering. Finally nature assembles components at low energy cost, teaching lessons in processing. Biomimetics thus became a fashionable topic covering projects ranging from the design of a shield inspired by the layered structure of the abalone shell to the development of genetically engineered materials such as artificial spider silk. More importantly, biomaterials inspired the emergence of a new style of chemistry, *chimie douce,* concerned with reactions at ambient temperature in open reactors resembling reactions occurring in biological systems.



114 Dialogo Secondo

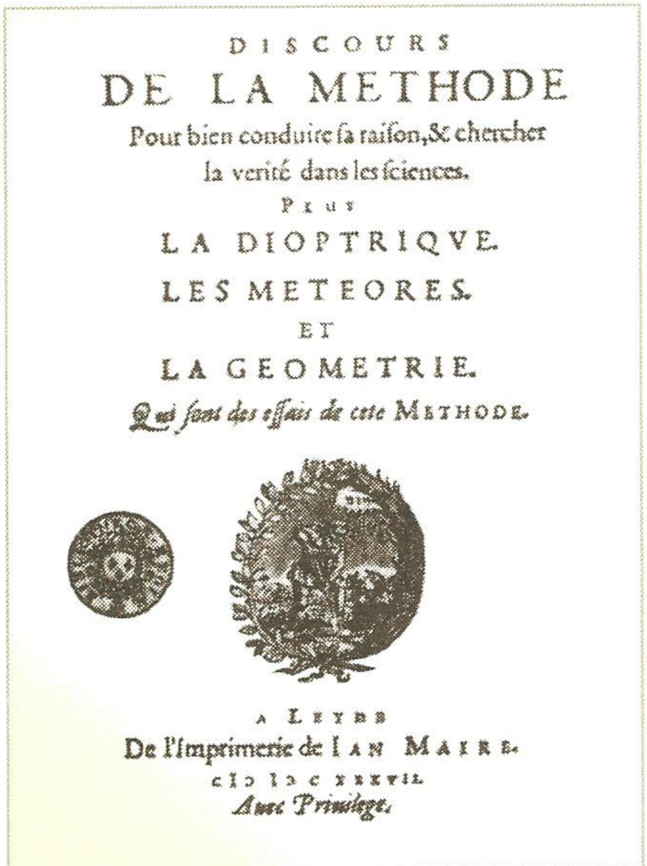
ſin quì dichiarate, non ſarà difficile l'intender la ragione, onde auuenga, che vn Priſma, ò Cilindro ſolido di vetro, acciaio, legno, ò altra materia frangibile, che ſoſpeſo per lungo ſoſterrà graviſſimo peſo, che gli ſia attaccato, mà in trauerſo (come poco fà diceuamo) da minor peſo aſſai potrà tal' volta eſſere ſpezzato, ſecondo che la ſua lunghezza eccederà la ſua groſſezza. Imperò che figuriamoci il Priſma ſolido A B, C D *fitto in vn muro dalla parte* A B, *e nell' altra eſtremità s'intenda la forza del Peſo* E, *(intendendo ſempre il muro eſſer eretto all' OriZonte, & il Priſma, ò Cilindro fitto nel muro ad angoli retti) è manifeſto che douendoſi ſpezZare ſi romperà nel luogo* B, *doue il taglio del muro ſerue per ſoſtegno, e la* B C *per la parte della Leua, doue ſi pone la forZa, e la groſſezZa del ſolido* B A *è l'altra parte della Leua, nella quale è poſta la reſiſtenza, che conſiſte nello ſtaccamento, che s' hà da fare della parte del ſolido* B D, *che è fuor del muro, da quella che è dentro; e per le coſe dichiarate il momento della forza poſta in* C *al momento della reſiſtenza che ſtà nella*

A diagram illustrating Galileo's theory of the strength of beams, from his *Two New Sciences* (1638)

Nanotechnology and biomimetics disrupt rather than reinforce the fragile coherence of the mixed discipline of MSE. The field is imploding. Its territory is dismembered into many research areas concerned with different scales and kinds of structures. The frontiers of MSE border bio-engineering and artificial intelligence. Materials scientists follow divergent epistemic practices. Some advocate rational design by computer simulation. They want to build up a material by computer calculations *ab initio,* starting with the most fundamental information about the atoms and using the most basic rules of physics. Others apply a combinatorial approach, developed initially in the pharmaceutical industry. It calls for the simultaneous synthesis of a large array of compounds at once, screened to detect and select interesting structures. Despite their differences, both strategies look exceedingly systematic when compared with the semiempirical methods chosen by scientists who encourage new materials to assemble themselves. Again two different pathways may be distinguished. Some scientists engineer bacteria, while others try the chemical route. Whether materials science will split into branches integrated into established disciplines or become a discipline of its own, pioneering a new style of science, the future will tell. Meanwhile MSE functions as a laboratory to test new frontiers in science.

Bernadette Bensaude-vincent

MECHANICAL PHILOSOPHY. Many seventeenth-century natural philosophers sought to explain all physical properties and processes in terms of the motion of the least parts of



DISCOURS
DE LA METHODE
Pour bien conduire ſa raiſon, & chercher
la verité dans les ſciences.
PLUS
LA DIOPTRIQUE.
LES METEORES.
ET
LA GEOMETRIE.
Qui ſont des eſſais de cete METHODE.

A LEYDE
De l'Imprimerie de IAN MAIRE.
CIϽ IϽ C XXXVII.
Avec Privilege.

Title page of the *Discourse on Method* (1637) and its illustrative essays by René Descartes. The essays sketch out a mechanical and mathematical world view.

matter of which physical bodies are composed. They usually referred to these least parts as corpuscles so as not to confuse the mechanical position with the type of ancient atomism that Pierre Gassendi had tried to revive early in the century. Although the mechanical philosophers (or corpuscularians) agreed in rejecting Aristotelian philosophy and most of the mystical elements associated with Renaissance naturalism, they divided over the positive formulation of their position. "Mechanical philosophy" is a cover term for a continuum of positions from a pure kinetic theory of motion on one end to a robust matter theory on the other. These variations can be seen in the works of René Descartes, Francis Bacon, Galileo, Robert Boyle, and Isaac Newton.

Descartes maintained in his *Discourse on Method* (1637) that matter is pure extension, from which it followed that there could be no empty space; that all motion must result from direct contact; and that all change must be change of place (local motion). Descartes concluded that any property possessed by a material body had to arise from the motion imposed on the matter it contained by an external source. All physical processes, therefore, were to be explained by the laws of motion that the least parts of matter obey. Only the human soul escaped mechanical explanation. The world was a vast machine made up of smaller machines (including human and animal bodies) consisting of inert particles moved by physical necessity. Although Descartes located the origin of motion in God, his principles of inertia and the plenum allowed him to describe a deterministic system where, on impact, motion is transferred but not destroyed.

Cartesianism dominated corpuscularism throughout the seventeenth and into the eighteenth centuries, but it had several strong competitors. In his *Novum organum* (1620), Bacon advocated explanations in terms of the motion of matter. In his investigation of heat, for example, he concluded that bodies feel warm when the particles of matter that compose them move rapidly. Unlike the later Cartesians, however, Bacon insisted that experimental and observational techniques had to be developed to discover the true nature of the particles responsible for such qualities. Galileo's *Assayer* (1623) offered a similar account of motion as the cause of heat, and his *Discourse on the Two New Sciences* (1638) presented detailed experimental studies of mechanical subjects. Both Bacon and Galileo brought the practices of craftsmen and mechanics to bear on natural philosophical issues. In this tradition, the mechanical philosophy helped to elevate the intellectual, social, and economic status of the technical arts.

Many natural philosophers in England in the generation after Bacon took his works as their model. Boyle followed Bacon's experimental program and believed in the Baconian ideal of useful knowledge. Writing in the 1660s, Boyle was also influenced by the works of Descartes, Gassendi, and Galileo, and introduced the term "mechanical philosophy" in 1674 to refer to all explanations of physical phenomena in terms of matter and motion. Unlike philosophers before him, however, Boyle tried to use chemical analysis to turn the mechanical philosophy into an experimentally based theory of matter. He also elaborated upon the distinction, first introduced by Galileo, of the primary and secondary qualities of bodies. In *The Origin of Forms and Qualities* (1666), Boyle maintained that quantifiable properties, such as size and shape, are primary because all material bodies possess them. Other qualities, such as color or texture, arise in us in consequence of the particular configurations of corpuscles in the bodies that we see or touch.

Newtonian or classical mechanics is often taken as the paradigm of mechanical explanation. Yet in his *Principia mathematica* (1687), Newton upset the mechanical philosophy by introducing the concept of force. Unlike Descartes and Boyle, for whom force amounted to the pressure of one body on another, Newton's force was the measure of the change in motion of a moving body. Thus he added a third element to the original principles of matter and motion. At first mechanical philosophers, especially Cartesians, rejected Newtonian forces as a throwback to sympathies and antipathies. But his scheme gradually gained acceptance as mathematicians succeeded in deploying gravitational force to ever finer phenomena and other examples of distance forces turned up in electricity and magnetism.

Following Newton's achievements, mechanical conceptions came to be applied to all areas of learning, not always with advantage. Ernst Mayr, for example, in *The Growth of Biological Thought* (1982), argued that reliance upon mechanics advanced physical sciences but led to the neglect of the biological ones. This assessment can of course be extended to the human sciences as well. Sociologists and psychologists in the nineteenth and twentieth centuries often attempted to find deterministic laws covering the behavior of groups and of individuals.

At a more global level, some have argued that ecological disaster can be attributed, at least in part, to mechanistic ideas of nature. In *The Death of Nature* (1980), Carolyn Merchant put forward the still controversial thesis that with the mechanical philosophy scientific inquiry became a masculine activity imposed upon a passive, feminine nature. According to Merchant, this attitude set the stage for, and ultimately justified, the "rape" of nature.

ROSE-MARY SARGENT

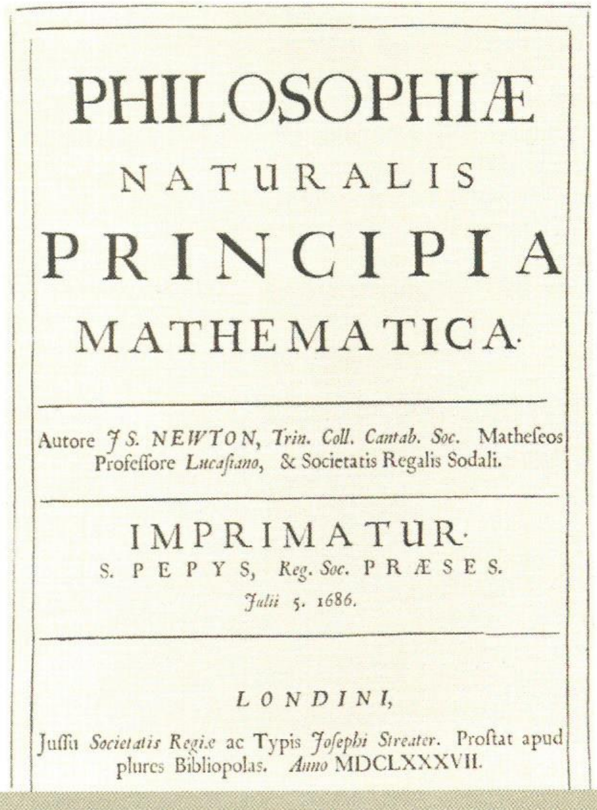
MECHANICS. If bodies move, forces move them; if they are in equilibrium, opposing forces hold them at rest; for mechanical devices to work, there must be forces of both sorts. Motion, forces, and machines have been the subject of two distinct sciences: the science of motion, and mechanics. In the Aristotelian tradition, the science of motion belonged to physics, or natural philosophy, the science of natural bodies "insofar as they are natural." Aristotle opposed natural motion (a falling rock) to violent motion (a weight raised by a pulley). Violent motions and the machines that created them were the concern of the mechanical arts—acting *against* nature for practical ends—and of mechanics, or the science of weights. The division of mechanics into manual or practical, and rational or theoretical, goes back to Pappus of Alexandria in the early fourth century A.D. and was current thirteen hundred years later.

The Renaissance inherited many important achievements in rational mechanics, including the parallelogram rule for the composition and resolution of motions, early forms of the principles of virtual work and of virtual velocities, demonstrations of the law of the straight and angular lever, an embryonic notion of moment (torque), and determination of centers of gravity. Equally important was the understanding that geometrical demonstration was essential to mechanical theory. This legacy underpinned the evolution of mechanics in the early modern period. Simon Stevin and Galileo simplified Archimedes' proof of the law of the lever; Christiaan Huygens devised a more rigorous proof (1693). Galileo used the angular lever and the notion of moment to determine equilibrium conditions on the inclined plane (*Le meccaniche,* c. 1593).

The parallelogram rule for motions uses geometrical displacements straightforwardly. Not so the corresponding rule for forces, because it is not obvious what their "composition" and "resolution" mean. Following the work of Stevin and others, Pierre Varignon based his theory of equilibrium on the rule for forces (*Projet de la nouvelle mécanique,* 1687). Isaac Newton recognized its indispensability, and cannily prepared for his own proof of the rule in the *Philosophiae naturalis principia mathematica* (1687) by stipulating in his second Law of Motion that every change in motion caused by an impressed force takes place "along the straight line in which the force is impressed." This ensured *by definition* the geometrical equivalence of the rules for forces and motions. As for the principle of work, Newton claimed that it depends on the equality of action and reaction (Law III). In René Descartes's formulation of the principle of mechanical work, the same force that raises one hundred pounds through two feet will raise two hundred pounds through one foot (and so on). This he used effectively in short treatises on machines he sent in 1637 to Marin Mersenne and Constantijn Huygens.

These examples belong to "rational mechanics" as understood by Pappus. They remind us that the major figures, better known for their contributions to the science of motion, also contributed to mechanics, though their thinking in these areas revealed the conceptual fluidity characteristic of pivotal transformations in the development of science. Two contrasting signs of this fluidity were the creative coupling of principles from both sciences, and indecisiveness about the relations between mechanics and physics. Galileo corroborated his law of free fall through experiments on the inclined plane, and the equilibrium conditions on the inclined plane played key roles in the formal demonstration of the law in the Third Day (or part) of his *Discourses concerning Two New Sciences* (1638). In the fourth part, Galileo used the law of fall and the composition rule to demonstrate the parabolic path of projectiles, a result he obtained and confirmed experimentally around 1608. Apart from certain medieval innovations in the geometrization of natural motion, natural philosophy had not been mathematical, whereas mechanics had never been anything else. Galileo decisively blurred that dichotomy by showing that natural motions could be given mathematical descriptions in accord with experiment and mechanical principles. Still, he would have agreed that *Le meccaniche* belonged in a different disciplinary pigeonhole from the third and fourth part of his *Discourses.*

In *Principia philosophiae* (1644), Descartes set out his pioneering three "Laws of Nature," according to which a bodily state persists until forced to change by external causes, a moving body endeavors to move always in a straight line, and exchanges of motion (size × speed) between colliding bodies are determined by the contests between their forces of persistence and by Descartes's conservation law. Descartes claimed that his laws and the collision theory derived from them could explain the whole physical universe, including machines. Yet there is nothing on mechanics in his *Principia,* nothing that explains the work principle of 1637. Christiaan Huygens's masterly solution to the problem of centre of oscillation (*Horologium oscillatorium,* 1673) required an insight from Galileo's *Discourses* (third part) enunciated as a principle by Evangelista Torricelli (1644): a system of heavy bodies cannot move of its own accord unless the common center of gravity descends. Torricelli's principle also played a crucial role in Christiaan Huygens's collision theory, out of which tumbled the result that in perfectly elastic collisions the quantity mv^2 remains constant. Huygens regarded this result as a notable corollary of his collision rules; to Gottfried Wilhelm von Leibniz it suggested the universal conservation of *vis viva,* a force measured by mv^2, to add to the already



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos
Profeſſore *Lucaſiano,* & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater.* Proſtat apud
plures Bibliopolas. *Anno* MDCLXXXVII.

Title page of Isaac Newton's *Principia* (1687), which laid down the laws of mechanics and applied them to various problems of motion, from bullets to planets known conservation of "directed motion." This confirmation of force as a metaphysical reality led Leibniz to the creation in 1691 of a new science of force, which he baptized *dynamics*. It led in turn to a protracted argument in the early decades of the eighteenth century about whether motive force should be mv, the Cartesian and Newtonian measure, or mv^2, the Leibnizian measure.

Newton transformed Descartes's "Laws of Nature" into three "Axioms" or "Laws of Motion" according to which a body persists in its state of rest or straight-line motion (Law I), the force impressed on a body is proportional to its change of motion (Law II), and action and reaction are equal and opposite (Law III). From these laws Newton demonstrated the mutual dependence of his inverse-square law of universal gravitation and Johannes Kepler's first and third laws of planetary motion—the second law being a consequence of inertial motion under any central force. The basic problem—to determine the central force given the planet's deviations from inertial motion summed as an orbit, and conversely—was quite foreign to traditional mechanics. Although in the *Principia* Newton links Law III to the work principle and proves the parallelogram rule for forces (which is "abundantly confirmed from mechanics"), the *Principia* is not a treatise on mechanics, but on "the mathematical principles of natural philosophy."

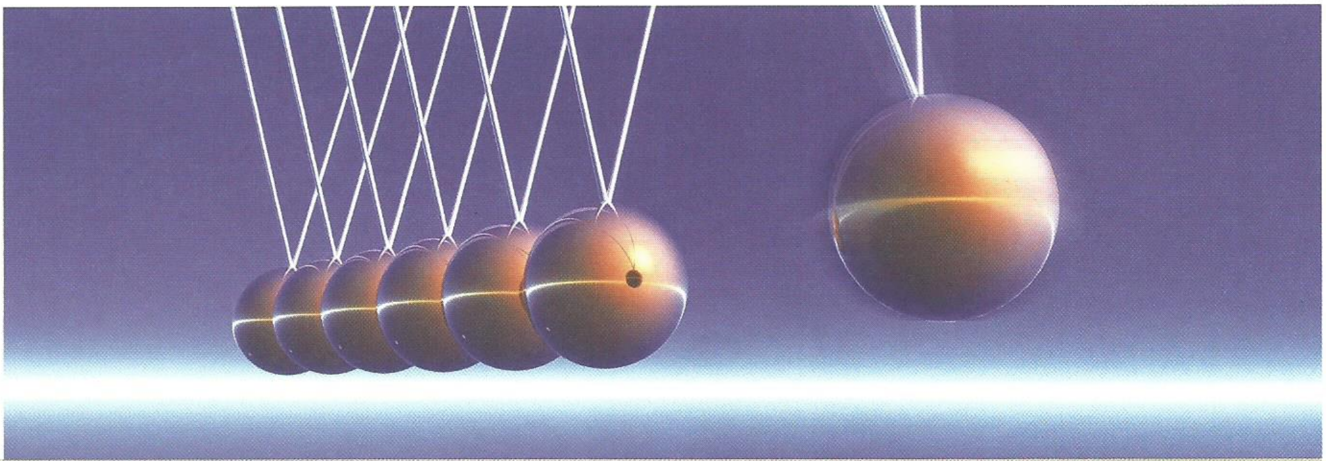
However, Newton's *Principia* was a major exercise in rational mechanics in a new sense that emerged in the work of Isaac Barrow and John Wallis. Barrow had argued (1664–1666) that geometrical theorems apply to all of physics, so that the principles of mechanics and of physics become identical. For Wallis, mechanics was "the part of geometry that deals with motion, and investigates, apodictically and using geometrical reasoning, the force with which such and such a motion takes place" *(Mechanica,* 1670–1671). Similarly, for Newton rational mechanics was "the science, set out in exact propositions and demonstrations, of the motions that result from any forces whatever and of the forces that are required for any motions whatever" *(Principia,* "Preface"), and natural philosophy was basically the problem of "finding the forces of nature from the phenomena of motions and then to demonstrate other phenomena from these forces." The same ideas were to inform Leonhard Euler's *Mechanica* (1736), significantly subtitled *The Science of Motion Expounded Analytically.*

"Rational" or "theoretical" mechanics in the older sense should be distinguished from the post-Newtonian sense of "rational mechanics," which comprised dynamics and statics. Mechanics in its golden age (the eighteenth century) was not merely a set of variations on the principles and methods of Newton's *Principia.* Among additional ingredients were the concepts and symbolism of Leibnizian differential and integral calculus, which became standard in treatises on analytical mechanics of the period, and the new mathematics, particularly the calculus of variations, which made it possible to formulate new principles that solved new problems.

To take some notable examples, a general theory of rigid-body motion became a desideratum following the work on centers of oscillation of Huygens, Jakob Bernoulli (1703), and Jean d'Alembert (*Traité de dynamique,* 1743), and the researches on lunar libration and equinoctial precession by Newton (*Principia*), d'Alembert, and Joseph Louis Lagrange. Here the principal figure was Leonhard Euler (memoirs of 1750, 1758), whose *Theoria motus corporum solidorum seu rigidorum* (1760) provided a general theory of rigid-body motion. Euler's researches depended on a "new principle of mechanics" (1750), his recasting of Newton's Law II in the analytic form $mdv_{x,y,z} \propto f_{x,y,z}\, dt$. Euler introduced moment of inertia (1749) and principal axes of rotation (suggested by the rolling of ships about three orthogonal axes), which he applied in his theory of the spinning top, an exceptionally difficult problem that had not even been recognized as a problem since the early seventeenth century.

Suppose in a system of bodies in mutual constraint the motion applied to each body a_i resolves into the motion actually acquired v_i and another motion V_i. That is the same as if the v_i and V_i had initially been communicated together, so that the system would have been in equilibrium had the V_i alone been present. That is "d'Alembert's Principle," the centrepiece of his *Traité de dynamique,* which allowed the methodological reduction of dynamics to statics. Lagrange reformulated the principle and coupled it with the principle of virtual velocities to obtain the first formulation of what became "Lagrange's Equations" (*Mécanique analytique,* 1788). Lagrange showed that the conservation of linear and angular momentum, and of *vis viva,* and the principle of least action, follow from his equations, rather than being foundational principles in their own right.

Pierre de Maupertuis's principle of least action had sounded a new note. Reflecting on the controversy of the 1660s over Fermat's least-time optical principle, Maupertuis argued (1744) that in all bodily changes, the "action" (Σ mass × speed × distance) is the least possible, a principle that for Maupertuis and Euler—though not for d'Alembert and Lagrange—pointed to the gover-



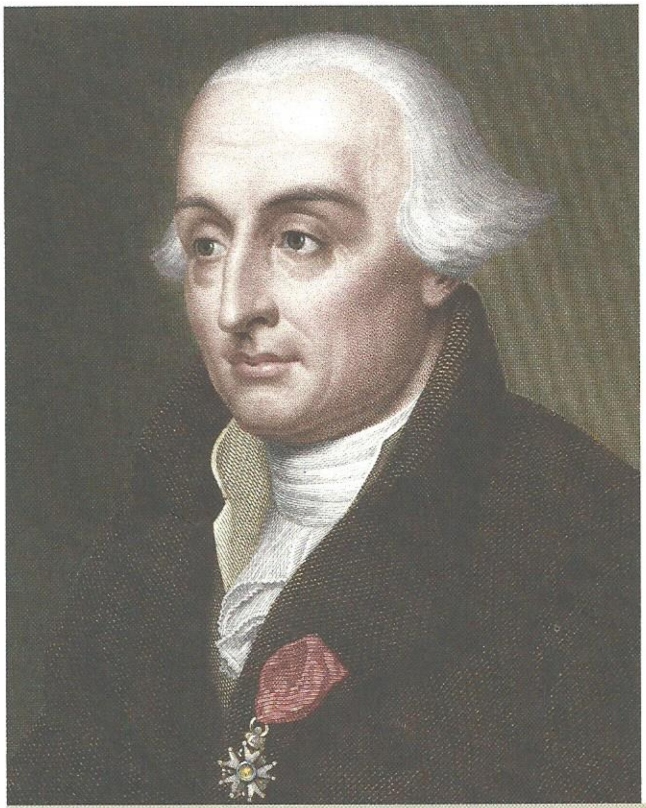
"Newton's cradle," a standard teaching apparatus of the 18th century, illustrates the conservation of momentum.

nance of all things by a Supreme Being. (Σ signifies a sum over all particles in the system under consideration.) Given the principle of virtual velocities, Σ force × ds = 0, which means, by the principles of the integral calculus, that the integral of this sum is a maximum or minimum. Euler developed the least action principle clearly and rigorously for a single particle (1744), and, in a memoir on lunar libration (1763), Lagrange extended Euler's result to an arbitrary system of bodies and derived a general procedure for solving dynamical problems.

The nineteenth century saw new departures in the application of principles established in the preceding two centuries. The relativity of motion, a central theme since the work of Galileo and Huygens, became the object of further study in the work of Alexis-Claude Clairaut, who asked how a system of moving bodies would behave if the system moved along noninertial curves (1742). Gaspard Gustave de Coriolis showed (1835) that the Newtonian laws of motion apply in a rotating reference frame if the equations of motion include a "Coriolis acceleration" in a plane perpendicular to the axis of rotation, a kinematic acceleration which Coriolis interpreted as an extra force (the "Coriolis force") and which became important in ballistics and meteorology. An important step in the formalization of mechanics was Heinrich Hertz's attempt to remove inconsistencies arising from the assumption within traditional classical mechanics that forces are ontologically prior to the motions they cause. He treated forces as "sleeping partners" in a formalized mechanics that depended on the operationally understood notions of time, space, and mass, and when necessary on linkages to hidden masses with hidden motions with respect to hidden coordinates (*Die Prinzipien der Mechanik,* 1894).

Maupertuis's variational principle enjoyed an improved mathematical treatment by William Rowan Hamilton (1834,1835), whose transformation of Lagrange's equations was modified and generalized by Carl Gustav Jacobi in the form now known as the Hamilton-Jacobi Equation (1837). In turn, the Hamilton-Jacobi Equation found fruitful application in the establishment of the quantum mechanics of Louis de Broglie (1923) and Erwin Schrödinger (1926).

ALAN GABBEY

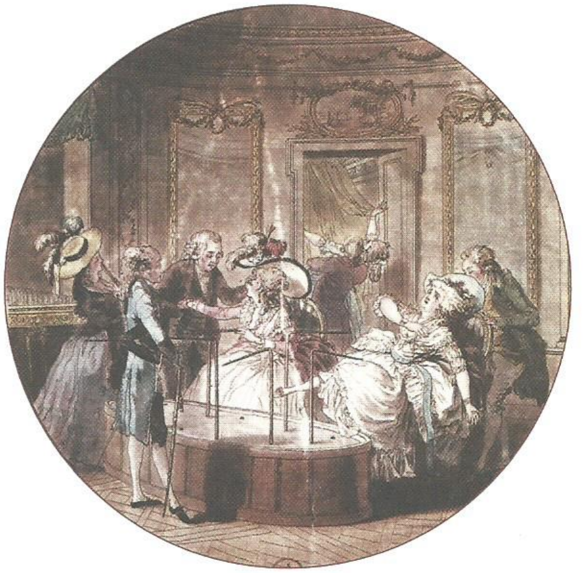


The French-Italian mathematician Joseph-Louis Lagrange (1736–1813), author of *Mécanique analytique* (1788), a formulation of mechanics of very wide application

MESMERISM AND ANIMAL MAGNETISM. Mesmerism was the creation of the Viennese physician Franz Mesmer, who regarded his technique of "animal magnetism" as an application of Newtonian principles to physiology. His doctoral dissertation at the University of Vienna concerned the influence of the Moon and planets on the human body, the idea being that the movement of the universal ether had an effect on health. He argued that the body required a certain quantity and rhythm of ethereal motion; disorders arose through an imbalance or incorrect type of motion.

Mesmer tried out this "tidal" theory of physiology in his medical practice in 1773–1774. He found that the application of magnets established an "artificial tide" in a patient. She initially reacted with pain, then improved dramatically. After this first therapeutic success Mesmer extended the practice to patients of all kinds. He could treat several at once by using a structure called a "bacquet," a circular tub studded round the edges with metal rods. Patients held fast to the rods, from which the magnetic influence supposedly flowed.

Mesmer's hometown of Vienna proved less receptive to his ideas than Paris. There his practice drew crowds of patients from the nobility. Magnetic clinics sprung up throughout France, although orthodox doctors and natural philosophers remained skeptical. Several of his pupils became prominent magnetists in their own right—Charles d'Eslon, Nicolas Bergasse, and Guillaume Kornmann among them—and mesmeric societies sprang up across the country. The success of Mesmer and his protégés drew the attention of the Paris Faculty of Medicine and the Royal Academy of Sciences, each of which appointed a commission to investigate. The commissioners attended magnetic clinics and tried the bacquet. Some of them experienced strong effects; others, nothing. Some of



The Austrian doctor Franz Mesmer (1734–1815) professed to be able cure people of most diseases by stimulating their animal magnetism. The experience sometimes sent patients, usually women, into a trance. The illustration dates from 1785.

the commissioners suspected that imagination might play a role in the phenomena. To test this, they persuaded a number of patients to believe they were being magnetized when in fact they were not (and vice versa). The magnetized patients exhibited no effects, while the unmagnetized patients experienced the expected "crisis." The commissioners concluded that although the phenomena were real, no physical agency caused them. Since the imagination was not then considered a legitimate cause of natural phenomena, attributing to it the mesmeric phenomena amounted to a form of dismissal. Mesmer lost control of the movement after this point, and several historians have suggested that he went mad.

Initiative passed to the marquis de Puysegur, who transformed mesmeric phenomena in one crucial respect. Before his time, mesmeric effects had been brief and violent, followed by a transformation in the patient's physical comfort. Puysegur produced a different phenomenon: an altered state of mind. In this lucid trance the patient said and acted in ways that seemed to indicate the presence of new mental powers. Subjects displayed signs of clairvoyance, foretold the future, diagnosed their own and other peoples' diseases, and spoke languages they had never learned. This new form of the mesmeric state could be used as a flexible tool for psychic and medical experimentation.

Mesmerism spread and diversified throughout Europe in the early nineteenth century, and many mesmeric societies and clinics were founded. In France, it again became a serious contender for scientific and medical respect, based on the work of Puysegur and of other major advocates such as Joseph Philippe François Deleuze and, from the 1830s, Charles Dupotet. In the 1820s, another royal commission investigated the practice, with mixed results—validating some effects, failing to reach consensus on others. Meanwhile mesmerism became well established in Germany and Switzerland; its more influential advocates included Johann Kaspar Lavater, Christoph Wilhelm Hufeland, and Carl Kluge. It took hold in Britain in the 1830s, a little later than on the Continent. Throughout the 1840s and 1850s it remained prominent in British public and medical discussion, and in 1842 its advocates could claim that they had used the mesmeric trance to create the first widespread surgical anesthetic (the first operation using ether anesthesia took place in 1846).

Medical mesmerism declined as an organized and prominent force in the second half of the nineteenth century, partly because of the proliferation of related sciences of mind. Hypnotism, for instance, was created as an alternative to mesmerism in 1842 and the spiritualist movement, which began in the 1850s, included many mesmeric elements. By the twentieth century the practice had been entirely subsumed within hypnotism, leaving only its terminology in popular usage. At that stage the terminology came to refer to fascination, charisma, and sex appeal rather than to a formal state of altered consciousness.

ALISON WINTER

A calorimeter is used to measure oxygen consumption, and thus resting metabolic rate, the number of calories a person burns per day at rest.

METABOLISM designates the totality of the chemical changes that take place among the constituents of living organisms.

The Hippocratic physicians called the conversion of food to the humors of the body "coction" by analogy with cooking. The analogy served as the basis for imagining the underlying process until the seventeenth century. As Greek anatomists from Aristotle to Galen described the internal organs of the body in increasing detail, they came to see nutrition as a sequence of similar transformations taking place from the mouth, through the stomach and intestines, and into the blood vessels, progressively changing into blood, the final nutritive fluid. The old anatomists also knew that the body continuously lost matter, not only through excretions, but also through "invisible transpiration." One of the earliest recorded experiments was an effort to measure the loss by comparing the quantity of food taken in by a bird with that accounted for in its solid excretions.

The systematic study of these exchanges goes back to the experiments of the Venetian physician Santorio Santorio, who, in the early seventeenth century, weighed himself on a large scale together with his food and excretions. From the differences measured daily over a very long time, he determined the quantity of matter lost through his skin and lungs in "insensible perspiration" and its variation according to internal and external factors.

During the seventeenth and eighteenth centuries, the nutritional exchanges of the body began to be explained by analogy with acid-alkali reactions, or fermentations, studied by the emerging science of chemistry. Often such transformations were referred to as composing the "animal economy," a phrase derived originally from analogy with the management of a household. A wholly new understanding of the overall significance of these exchanges came with the theory of Antoine-Laurent Lavoisier that respiration is a slow combustion yielding heat and work. Lavoisier thus explained the continuous food supply as a replenishment of carbon and hydrogen continuously consumed.

The rapid development of "plant" and "animal" chemistry in the early nineteenth century, and their fusion into the emerging field of organic chemistry, provided more robust foundations for investigating the chemical changes in living organisms. By the 1840s, the term "Stoffwechsel" had emerged as the preferred designation of these processes in German literature; its most common English translation, "metamorphosis," had previously been used both in German and English to describe the multiple chemical reactions, mainly partial decompositions, that organic compounds can undergo in the laboratory.

In his well-known treatise on the cell theory, Theodor Schwann introduced the adjective *metabolische* to signify the phenomena of chemical change that cells can produce either on molecules within themselves or in the surrounding fluids. French texts began in the 1860s to translate *Stoffwechsel* as *le métabolisme.* Michael Foster adopted the word "metabolism" in his textbook of physiology in 1878, and it soon afterward became the standard term in English.

Throughout most of the nineteenth century, efforts to define the intermediate chemical reactions that connect the foodstuffs entering the body with final decomposition products amounted to conjectures based on knowledge of the chemical properties of the substances involved. The experimental study of the *Stoffwechsel* consisted of quantitative measurements of the intake of carbohydrates, fats, proteins, and oxygen, and of the excretions in the form of urea, carbon dioxide, and water, according to different dietary regimens in health and disease. In 1904, Franz Knoop fed dogs a diet of phenyl-substituted fatty acids. The animals metabolized these compounds only with difficulty, with the result that they excreted some intermediate breakdown products. In this way, Knoop established that fatty acids are decomposed by a succession of "β-oxidations," each shortening the carbon chain by two atoms. This was the first experimentally established sequence of intermediate reactions; unfortunately, Knoop's method did not work for other reactions. During the next three decades, Knoop insistently advocated the view that the goal of biochemistry was to establish the complete sequences of decomposition reactions connecting foodstuffs to final end-products and the synthetic reactions producing body constituents.

During the first decade of the twentieth century, investigators found more direct methods of studying the chemical changes that take place between the beginning and end points of metabolism, and a new subspecialty, increasingly called "intermediary metabolism," began to take form. Federico Batelli and Linda Stern in Italy, and Thorsten Thunberg in Sweden, independently devised manometric methods to examine the phenomena in isolated tissues by testing the effects on their rate of respiration of adding substances suspected of being intermediates. Gustav Embden in Germany and others studied similar problems by means of perfused isolated organs. They identified a number of substances, such as pyruvic acid, acetic acid, and several dicar-boxylic acids, that must take part, but could not connect them and other suspected intermediates into well-demonstrated reaction sequences. Meanwhile, the achievement of cell-free fermentation by Eduard Buchner stimulated the study of the intermediate phenomena in yeast, which were more accessible to direct examination than animal tissues. A series of partially speculative fermentation schemes culminated in a sequence proposed by Carl Neuberg in 1913 in which hexose sugars broke down into methylglyoxal. The proposal guided investigators for more than a decade, until they showed that methylglyoxal played no part at all. By 1935, a modified sequence of reactions, resulting in particular from the work of Embden and Otto Meyerhof, defined the pathway of anaerobic carbohydrate metabolism.

In 1930, a young physician named Hans Adolf Krebs entered the field of intermediate metabolism, bringing with him methods that he had learned from Otto Warburg. Krebs discovered a cyclic process in 1932 through which urea is synthesized in mammals. He went on to discover several other pathways, including most notably the citric-acid cycle of carbohydrate metabolism in 1937. By then, individual pathways were beginning to link up in extended networks. The introduction of radioactive isotope tracers after 1940 accelerated progress in their identification. By mid-century, "metabolic maps" were complicated enough to fill large charts on biochemistry laboratory walls, and the main routes in the decomposition and synthesis of the amino acids, sugars, fatty acids, nucleic acids, and their many derivatives seemed nearly complete. Investigators began turning their attention to the question of the regulation of the pathways to maintain steady states while responding to the changing energy and other requirements of the organism, a quest that occupies metabolic biochemists to the present day.

FREDERIC LAWRENCE HOLMES

METALLURGY may be defined as the extraction of metals from their ores, their working and processing, the study of their structure and the development of alloys.

Although metals had been extracted and shaped for thousands of years, it was not until the sixteenth century that Georgius Agricola, a physician working in a German mining district, codified known metallurgical processes. His posthumous publication, *De re metallica* (1556), became an important text for later metallurgists, although it was based on theory and observation rather than on practical experience. Agricola's contemporary, Vannoccio Biringuccio, who was the chief armorer of Siena, produced a practical guide to metallurgical techniques, *Pirotechnia* (1540), based on his own practical experience.

René de Réaumur published an account of the French iron and steel industry in the 1720s based on his own observations and experimental work. His memoirs on the art of converting iron into steel had a mixed reception. Some critics believed that he had little understanding of metallurgy, while others viewed him as one of its pioneers.

During the eighteenth century, major developments in iron and steel manufacture occurred in Britain. In 1709, Abraham Darby successfully used coke instead of charcoal to smelt iron ore. This made possible the production of cast iron in great quantities and the construction of major cast-iron structures such as the first iron bridge in the world, a 100-foot span across the River Severn (1779). Benjamin Huntsman invented the crucible process for making steel in 1740, and Henry Cort developed the puddling process for the conversion of pig iron into wrought iron in 1784.

Sir Henry Bessemer's patented process of 1856 made possible the bulk production of cheap steel. A decade later, the German engineer Carl Wilhelm Siemens introduced the open-hearth furnace into Britain, while Emile Martin and his son Pierre did the same in France. This process could melt scrap steel, leading to the production of large quantities of high-quality structural steel, fundamental to the worldwide expansion of the railways and mass transportation.

In 1854, Henri-Ètienne Sainte-Claire Deville introduced a method for the commercial extraction of aluminum from bauxite. At first, aluminum was a luxury metal, and Napoléon III had a banqueting set made from it. In 1886, the American Charles Hall and the Frenchman Paul Héroult, working independently, found that aluminum oxide could be dissolved in molten cryolite and the aluminum extracted by electrolysis. This method is still in use today.

Metallography, the study of metal surfaces, has proved particularly important to metallurgy's development. Between 1863 and 1865, Henry Clifton Sorby examined the surfaces of polished and etched specimens of steel under the microscope, the results being referred to as microstructures.

Steel is a complex alloy, based on iron with varying amounts of carbon. Steel has a number of phases which are visible in the various microstructures and which possess different physical and mechanical properties. Sorby's micrographic work on the structure of steel was confirmed by X-ray diffraction. An analytical technique that provides clues to the internal structure of a material, it helped to confirm the atomic structure of metals and other materials.

The American physical chemist Willard Gibbs proposed the phase rule in 1876 in a maze of mathematics and using a terse style difficult for most of his readers to understand. This rule defined and classified phase changes in metals and metal mixtures using the then new techniques of thermodynamics. A phase may be defined as a distinct homogenous material that can be physically separated from other parts of the system. This work prompted the development of phase diagrams that visually illustrate these changes.

By using metallography and phase diagrams, metallurgists could predict the phases present in alloys at different temperatures. This led to the development and understanding of the heat treatment of alloys—for example, the quenching and tempering of steels and the age-hardening of aluminium alloys, introduced by the German Alfred Wilm in 1906.

Subsequent advances in the theory of solids gave rise to the concept, associated with Geoffrey Ingram Taylor, that deformation in metals takes place by the movement of dislocations (defects in the atomic arrangement) through the crystalline matrix. This concept led in turn to an understanding of failure through creep, fatigue, and brittle fracture, and to the development of strengthening mechanisms in modern alloys. The movement of dislocations was later confirmed with the aid of the electron microscope. Subsequently, more powerful field-ion microscopes, and high-resolution electron and atomic-force microscopes, have enabled metallurgists to specify the position of individual atoms.

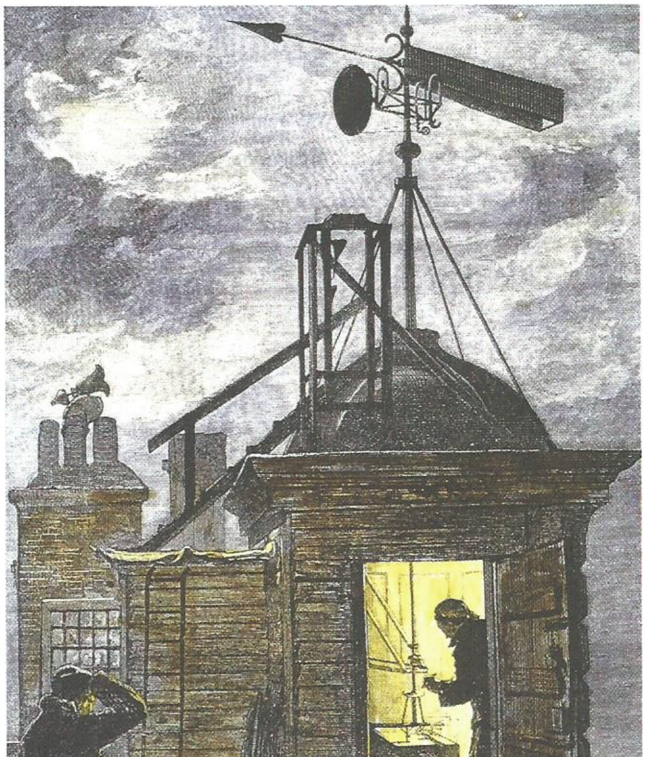
Willliam Hume-Rothery carried out definitive work on intermetallic phases, electron compounds, and metallic structures, and proposed rules regarding the solid solubility of metals. The development of solid state physics, quantum theory, and the theory of the periodic table have increased our understanding of the atomic structure of metals and their behavior.

In the late twentieth century, the development of the jet engine led to the demand for higher performance metals. A variety of light alloys, such as those based on aluminum and titanium, as well as superalloys (complex alloys that perform well at high temperatures), have been created for use in aerospace. Nanotechnology, the study and manufacture of materials and structures on the nanometer scale, and metal matrix composites are emerging as significant areas of metallurgical development in the twenty-first century.

Susan T. I. Mossman

METEOROLOGY. The history of modern meteorology begins with the Scientific Revolution. The late sixteenth and first half of the seventeenth century saw the invention of the meteorological instruments—thermometer, barometer, hygrometer, wind and rain gauges—and around 1650 natural philosophers began using them to record weather observations. They immediately understood the importance of coordinating observations over as wide a space as possible. Scientific academies solicited weather diaries and organized observational networks; Leopold de' Medici, Grand Duke of Tuscany, founder of the Accademia del Cimento, and Robert Hooke of the Royal Society of London both sponsored networks of observers in the 1650s and 1660s. They were motivated in part by theories deriving from the Hippocratic treatise *Airs, Waters, and Places* that related the weather to disease; for two and a half centuries meteorologists attempted to correlate weather patterns with epidemic outbreaks and climate with public health. The application of meteorology to agriculture provided further motivation. In addition, Enlightenment meteorology attempted to rationalize traditional weather lore, including astrological meteorology, searching through recorded observations for patterns confirming traditional wisdom.

Among the few attempts at a theoretical understanding of weather phenomena were explanations of the trade winds by Edmond Halley and George Hadley. According to them, the rising mass of heated equatorial air is replaced by an inflow of cooler air from higher latitudes. This north-south circulation is deflected, according to Halley, by the movement of the subsolar point with the earth's diurnal motion, or, in Hadley's theory, by the acceleration we now call Coriolis. A flow of warm air at high altitude from equator to poles completes these early pictures of the general cir-



Weather station at the Royal Observatory, Greenwich, in 1880 culation. They illustrate the role of oceangoing commerce both as a source of data and incentive for meteorology.

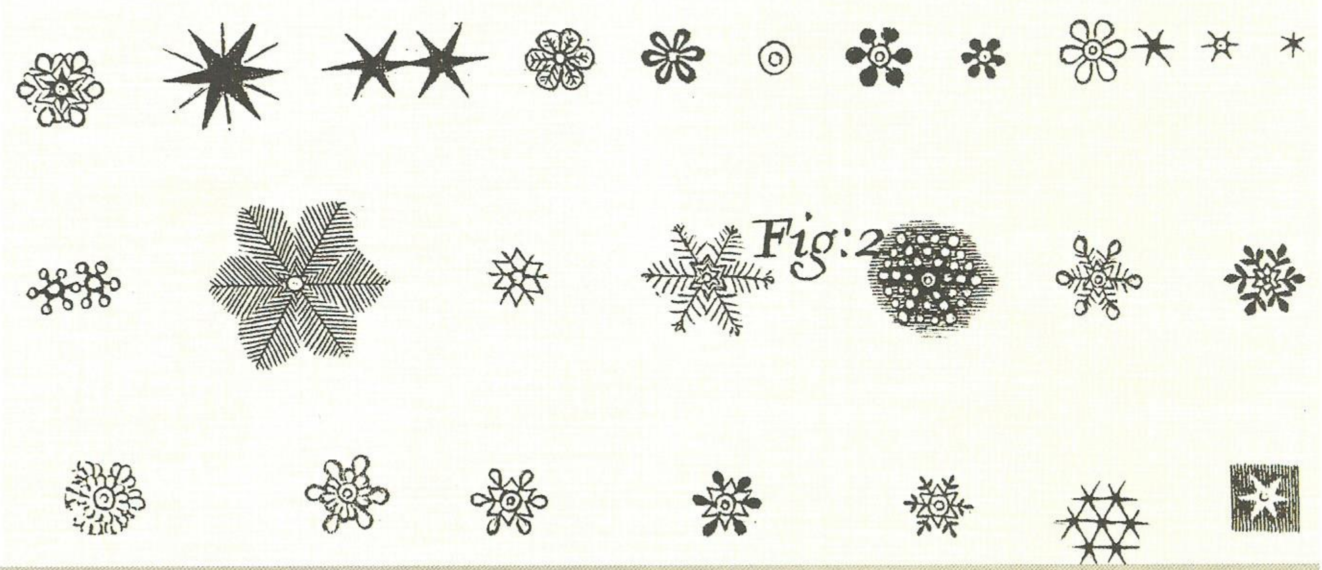
Early modern meteorologists were frustrated by observers' lack of discipline and by the poor quality of instruments, which rendered observations nearly useless. The late Enlightenment resolved these problems. Emerging modern states organized large networks of disciplined observers, instrument makers developed precise instruments of all types, and natural philosophers devised methods of systematic measurement. By the end of the eighteenth century meteorologists had access to large quantities of reliable weather data for the first time.

Enlightenment meteorologists, seeking weather patterns and correlations with agricultural harvests or outbreaks of disease, lacked a sense of the geographical expanse of weather events and of their development over time. Romantic natural philosophers worked out geographical and temporal syntheses. Alexander von Humboldt's famous isothermal lines synthesized temperature observations over the globe; Humboldt integrated all the factors of climate into a unified science of the earth that he called "physique générale." Heinrich Wilhelm Brandes drew (or perhaps proposed to draw) synoptic maps of the weather over Europe for every day of 1783, tracing the progress of temperature changes across the Continent, uncovering the geographic distribution of barometric pressure, and relating wind direction to barometric differences. In the 1830s meteorologists took up the kinetics of storms. Heinrich Wilhelm Dove's "Law of Gyration" described the veering of storm winds resulting, he argued, from the conflict of equatorial and polar air currents; William C. Redfield insisted on the rotary motion of storms. James Espy introduced thermodynamic considerations, pointing to the adiabatic cooling of rising moist air and the energy of latent heat released in precipitation as the "motive" force of tropical storms.

The advent of the telegraph around midcentury made possible the nearly immediate collection of meteorological data on a continental basis; at the same time, the growing importance of meteorology for agriculture and oceangoing commerce led governments to establish national weather services to coordinate observation, particularly for storm warning. The resulting inflow of data fed the systematic production of synoptic weather charts, which became important research tools. A community of meteorologists evolved, its members more consistently trained in physics and mathematics, while the discipline acquired journals and professional societies. These factors, along with the emergence of thermodynamics after midcentury, led to quantitative treatment of Espy's supposition. A consistent body of work emerged, known as the "thermal" or "convective" theory of cyclones, that derived the kinetic energy of storms from the release of latent heat and the adiabatic cooling of rising currents of air. William Ferrel applied hydrodynamics to the process, showing that air movement caused by any chance pressure gradient will be bent into a spiral by the earth's motion, generating a barometric low and the beginnings of a storm system. Hermann von Helmholtz and Vilhelm Bjerknes were the best known among scientists applying hydrodynamics to meteorology.

Around the turn of the twentieth century, balloons, kites, and airplanes made available observations of the upper atmosphere, while aviation generated demand for detailed forecasts in three dimensions. World War I sharpened these requirements. Discrepancies in the temperature distribution above storms had led meteorologists around the beginning of the century to consider the role of air masses of differing temperatures and geographic origin in the formation of storms. The polar front theory, developed immediately after the war by Bjerknes and his Bergen (Norway) school of meteorologists, demonstrated the origin of cyclones in the encounter of cool, polar air masses with warmer air. In the 1920s, the Bergen school extended the air-mass approach to weather not associated with storms.

Around the same time, Lewis Richardson succeeded in computing (after the fact) a six-hour advance in the weather using numerical algorithms. The effort consumed six weeks, generated disappointing results, and convinced meteorologists of the uselessness of a computational approach. The advent of the electronic computer during World War II encouraged a new attempt at computational forecasting. John von Neumann, who selected meteorology to demonstrate the computer's usefulness, had by 1956 shown that it could generate accurate forecasts. The computer has enabled meteorologists to exploit the immense quantities of data arriving from weather satellites and a greatly increased number of observational sources in the atmosphere and at



Snow flakes, as depicted by Robert Hooke in *Micrographia* (1665) the earth's surface. Computational models of the atmosphere have since blurred the distinctions among observation, experiment, and theory.

THEODORE S. FELDMAN

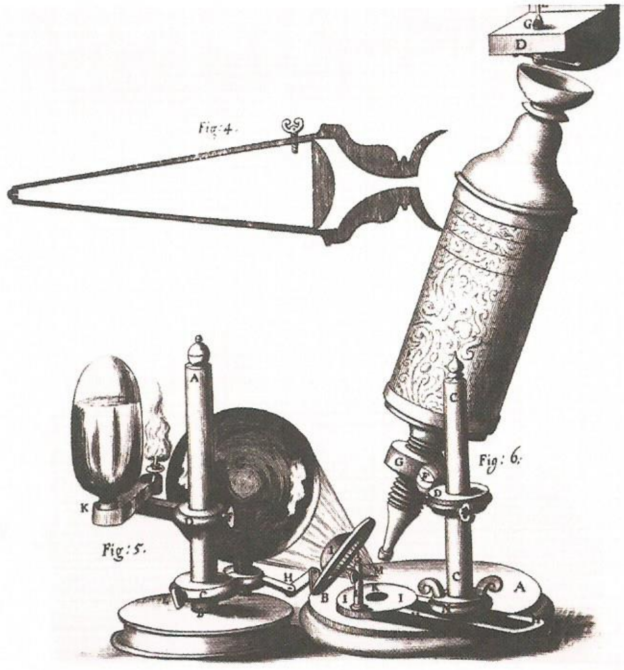
MICROSCOPE. The microscope is an instrument for obtaining an enlarged image of an object, which may be viewed directly, photographed, or recorded electronically. The number of times the investigated object appears enlarged determines the magnification of the instrument, and the resolving power specifies its capacity to distinguish clearly between two points.

The earliest simple light microscope consisted of a single lens framed by a ring, plate, or cylinder, combined with a device for holding the object and a focusing mechanism. The compound microscope consisted of a movable tube containing two lenses or lens systems, the objective forming an enlarged image of the object and the ocular or eyepiece magnifying it; a stand; and a specimen stage. Illumination was provided either by a mirror placed under the stage to reflect light into the instrument or by a lamp built into the stand.

The microscope probably was invented during the second decade of the seventeenth century since the earliest printed descriptions and illustrations of a microscopically observed object, the bee, appeared in 1625, in the *Melissographia* and the *Apiarium* published by members of the Accademia dei Lincei. Robert Hooke's enthusiastically received *Micrographia* of 1665 presented a lavishly illustrated survey of "minute bodies" ranging from the point of a needle and the pores of cork to bookworms and fleas. It also contained an analysis of methods of microscopy and a description of Hooke's compound microscope, an instrument with a single-pillar stand on a solid base and a tiltable tube. Other seventeenth-century microscopists, notably Antoni van Leeuwenhoek, Marcello Malpighi, and Jan Swammerdam, used simple microscopes. Leeuwenhoek made more than three hundred of them, small plates of metal encasing a lens with provisions for focusing, the majority magnifying between 75 and 150 times. Communicating his findings largely through letters to the Royal Society of London, he became known particularly for his observations of "animalcules" in sperm.

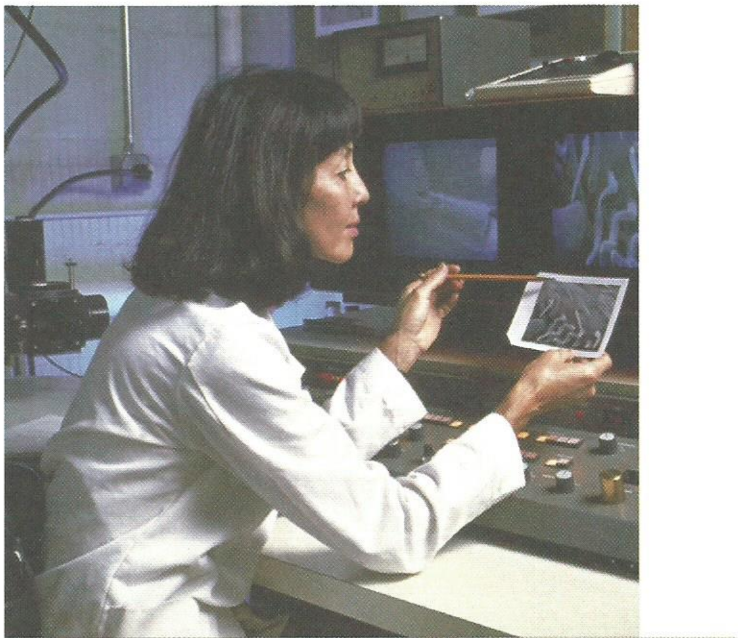
In the eighteenth century, investigators throughout Europe continued to use both simple and compound microscopes. Spherical and chromatic aberrations, however, impaired the performance of these instruments. Objects appeared blurred and surrounded by colored fringes, because a spherical lens surface brings the light rays passing through different parts of the lens to a focus at different points, and light rays of different colors are refracted differently. Reducing the aperture with a diaphragm could lessen the spherical aberration, but at the cost of dimming the image. The aberrations affect the compound microscope more strongly than the simple microscope.

Achromatic telescope objectives consisting of lenses combining crown and flint glass were first made in the later eighteenth century. Although manufacturing the smaller lenses of microscopes proved much more difficult, Joseph Fraunhofer and other instrument makers produced achromatic microscope objectives of low magnification by the early nineteenth century. After Joseph Jackson Lister showed in 1830 how to construct aplanatic objectives (achromats with minimal spherical aberration), achromatic instruments of higher magnification became widely available. Together with advancing preparation techniques, they greatly enlarged the scope of microscopy. Microscopists examining plant and animal tissue established the cell as the unit of life, thus transforming histology and pathology and massively stimulating microscopical investigation. Facilitated by the expansion of laboratory and academic science, microscopy became an integral part of medical education, diagnosis, and research, as well as a tool for organic chemistry and the physical sciences.



Microscope designed and employed by Robert Hooke (1635–1703), as depicted in his *Micrographia* (1665)

In 1873, Ernst Abbe published a theory of image formation that enabled the design of optically improved instruments. In the early 1880s, Abbe and Otto Friedrich Schott produced apochromatic objectives, which eliminated the residual secondary spectrum of the achromat and almost completely corrected both chromatic and spherical aberration. At that time, novel techniques



A technician demonstrates a scanning electron microscope at the University of California at Berkeley.

of staining and cultivation allowed the identification of pathogenic bacteria, which offered a potent new explanation of diseases.

In the late 1930s, the development of phase contrast microscopy, which utilizes the principles of diffraction to convert variations in optical paths into intensity variation, allowed the direct study of unstained transparent biological specimens. The illumination system improved with the incorporation of electric lamps in the 1930s, and again with the introduction of low-voltage tungsten-halogen lamps in the 1960s, which are now the norm. The light microscope has become ubiquitous. Current applications include routine medical tests and examinations of the surface quality of materials.

The twentieth century introduced new kinds of microscopes that utilize rays other than light. The electron microscope contains a source supplying a high-voltage electron beam, an evacuated column with electromagnetic fields along its length that act as a lens, a specimen stage, and an imaging system. In the transmission electron microscope (TEM), an electron beam passes through the object. In the scanning electron microscope (SEM), a comparatively small electron beam scans the object to produce an image of its surface.

The electronic engineers Max Knoll and Ernst Ruska constructed the first electron microscope in the early 1930s, utilizing contemporary cathode-ray technology, improved electronic tubes, and vacuum technology, as well as the quantum mechanical principle that the electron can be regarded as a wave. Ruska developed an instrument for commercial manufacture in association with a group of engineers at the electrical firm of Siemens in Germany. Their TEM entered the market in 1939, one year earlier than the TEM constructed by the physicist James Hillier and his group at the Radio Corporation of America (RCA). In 1948, Charles William Oatley at the University of Cambridge launched a research project to construct an SEM, which led to commercial production in 1965.

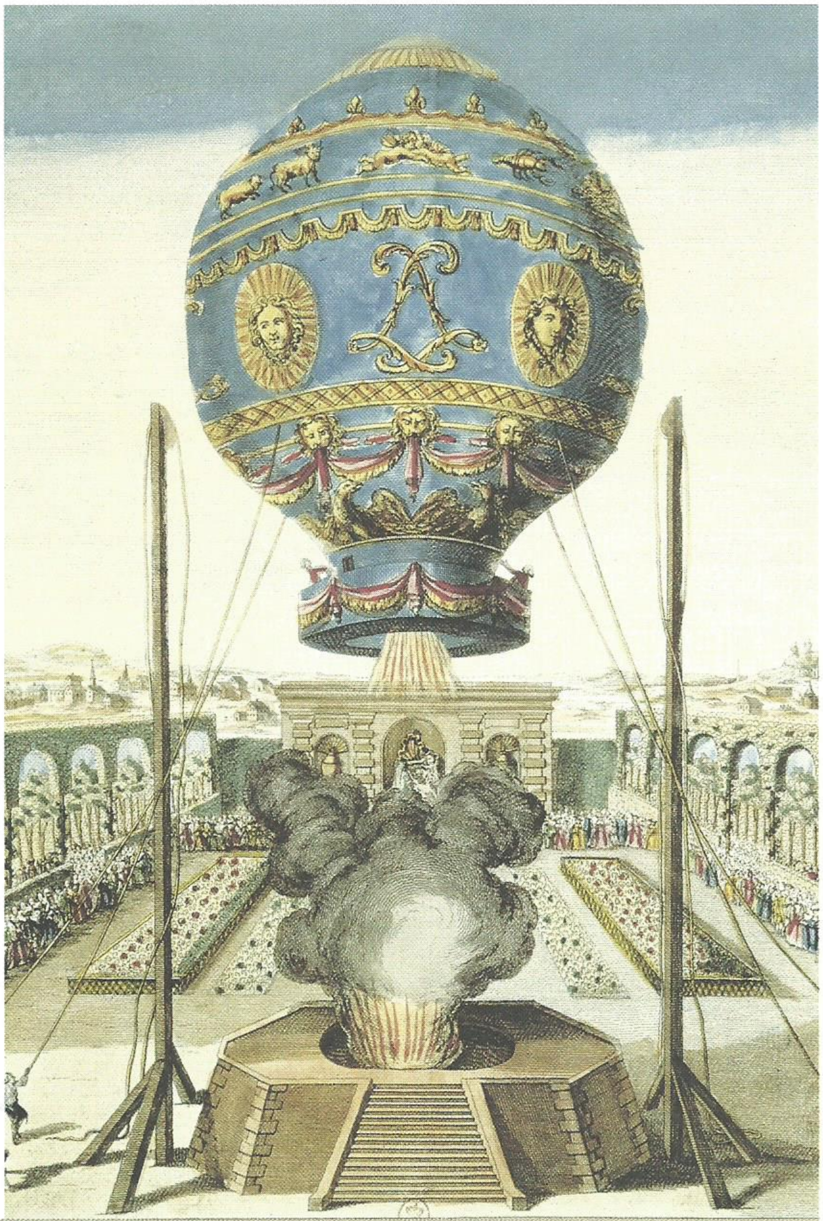
Both the biomedical and physical sciences use the TEM and SEM. The TEM requires elaborate preparation techniques. To maintain the vacuum, the specimens must be dehydrated; since electrons interfere strongly with matter, the sections must be extremely thin; and chemical fixation is needed to prevent alterations under the electron beam. The introduction of the ultramicrotome and plastic embedding material in the late 1940s facilitated preparation of delicate biological specimens, and rapid freezing has supplemented chemical fixation since the late 1960s. Preparation for the SEM, which can accommodate large specimens, is easier. Biological specimens are rendered conductive by metal coating; other specimens can frequently be investigated without preparation.

Current applications of the electron microscope include virus biophysics, polymer morphology, and materials characterization and inspection in semiconductor technology.

Jutta Schickore

MILITARY INSTITUTIONS. The contributions of science to warfare, especially to the wars of the twentieth century, are familiar to students of history. Not so well understood is the equal and opposite action: the influence of military institutions on science and technology. Although interest in the subject has mushroomed over the last decade, historians have not yet forged an overall synthesis. Recent research has focused on U.S. science during the Cold War, but older judgments regarding the two world wars need revisiting. Because the line separating science from technology has remained shifting and indistinct—thanks in part to military influence—"science" here stands for science and technology.

The early modern constellation of the sciences reflects a military influence. Early modern mathematics included disci-



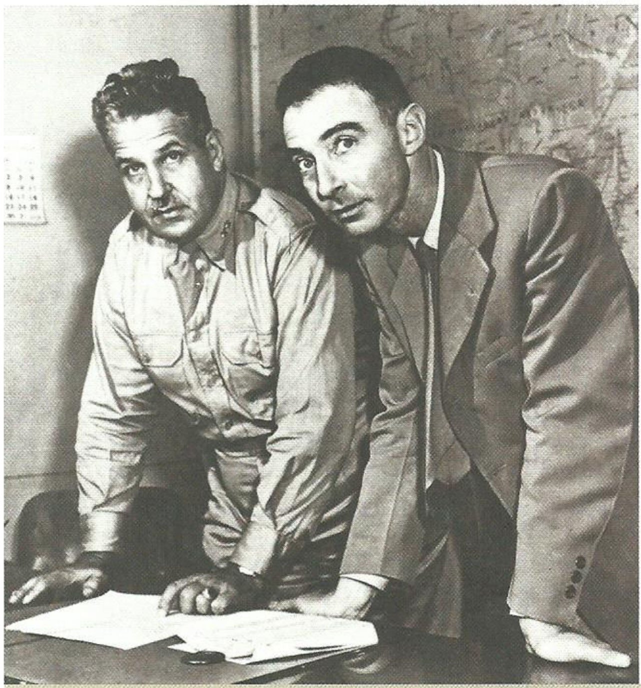
Not long after the invention of the hot-air and hydrogen balloons in the 1780s, they were adapted for military purposes and served as observation posts in the wars of the French Revolution. A 19th-century print of an 18th-century illustration of the launching of a montgolfière.

plines directly applicable to military affairs: fortification or military architecture, naval architecture, ballistics, cartography, and navigation. Early modern natural philosophy, on the other hand, included a broad range of nonquantitative subjects, from physics to botany and psychology; these pursuits offered little to the practice of warfare. Galileo Galilei consulted for the Venetian Arsenal, a naval institution, as a mathematician and courted the Medici family with a military compass. But when the telescope brought in his own ship he abandoned his career as a mathematician for the higher-status occupation of court philosopher.

Because mathematics was essential to the education of its military officers, the early modern state became an important patron of the subject. In France during the Ancien Régime, military and naval academies employed the top mathematicians of the age, including Gaspard Monge, who trained Charles Augustin Coulomb and Lazare Carnot. Carnot's technical contributions to French arms earned him the title "father of victories." Natural philosophy also received support as part of the cadets' general education. The Ecole Polytechnique, revolutionary successor of these institutions, produced much of the most important physics, mathematics, and engineering of the early nineteenth century. In the United States the Ecole's sister school, Thomas Jefferson's Military Academy at West Point, served as the only source of trained civil engineers for several decades and graduated military men who achieved international stature as scientists. In an era when military officers were broadly educated and mathematics included so much military content, mathematicians and engineers naturally found a home in military institutions.

Military support, intensifying after the Seven Years War, helped transform mathematics and natural philosophy. In France and England, national cartographic projects originated in military campaigns. These projects developed advanced methods of triangulation and measurement; along with other military and naval requirements, they generated intense demand for precise instruments. Profits from the sale of these instruments to armies and navies supported instrument makers' research and development and helped industrialize the scientific instrument trade; Jesse Ramsden's revolutionary instruments and his innovations in the organization and technology of instrument manufacture depended on his sale of sextants to the British Navy. At the same time, military engineers like Coulomb and England's William Roy crossed over into natural philosophy, applying mathematical techniques to fields like electricity, magnetism, and the study of gases, contributing to their quantification. Military needs and military engineers thus played an important role in the emergence of precise scientific instrumentation and in the quantification of physics in the late Enlightenment.

The early modern state also experimented with the mobilization of civilian scientists for military research. In France the monarchy employed members of the Royal Academy of Sciences in the reform of the manufacturing sector. Antoine-Laurent Lavoisier took on the gunpowder industry. Setting up a laboratory at the Arsenal in Paris—where he also carried out his more famous chemical researches—he developed methods of gunpowder manufacture that made France an exporter of high-quality gunpowder and laid the foundations of industrial chemistry. The Revolutionary government employed a number of Lavoisier's colleagues at a weapons laboratory at Meudon, where Claude Louis Berthollet and others developed incendiary weapons, explosive shells, and new types of gunpowder. The rediscovery of these explosive shells in the late 1830s revolutionized naval warfare.



Leslie Groves (1896–1970), head of the Manhattan Engineer District, with (on the right) J. Robert Oppenheimer (1904–1967), the director of the Project's Los Alamos laboratory, where the atomic bombs were designed

In the United States the army revolutionized manufacturing in the first half of the nineteenth century, developing at its national armories the so-called "American System": machine manufacture of weapons with interchangeable parts. Besides introducing modern methods of gauging and pattern replication, the army developed advanced business and accounting practices to manage its inventory and distribution requirements. The American System eventually took over much of American manufacturing and was eagerly received in Europe. Both the British Navy—in the case of the scientific instrument trade—and the American Army provided markets without which it would have been more difficult, if not impossible, to develop these technologies. No private arms manufacturer of the early nineteenth century would have undertaken as risky and pointless a venture as attempting to make weapons with interchangeable parts.

Closely related to military cartography was exploration, also often a military venture. James Cook earned his reputation charting the Saint Lawrence River for the Battle of Quebec. On his Pacific voyages he applied the most advanced techniques of land-based cartography to hydrography and contributed to the solution of the problem of longitude, which had long preoccupied the British Navy. Cook's voyages, part of a series of naval expeditions to the Pacific, set a precedent for the union of scientific and naval operations. The published goal of Cook's first voyage was the observation of the Transit of Venus—a purely scientific activity. But secret instructions charged Cook with establishing a foothold on the reputed Southern Continent and with surveying resources for naval stations and colonization. Cook carried with him civilian naturalists and artists who made important contributions to geography, botany, ethnography, and other sciences. Charles Darwin's *Beagle* voyage belongs to this same series of imperial hydrographical expeditions. In the United States the army, beginning with the expedition of Meriwether Lewis and George Rogers Clark (1803–1806), played a leading role in the exploration and conquest of North America. The expeditions of its topographical engineers, from the Revolution until their dissolution in 1853, ranged broadly through cartography, anthropology, geology, survey of natural resources, and diplomacy.

Notwithstanding its nurturing of manufacturing technology, the nineteenth-century U.S. military generally failed to appreciate the larger potential of science and technology for warfare. The navy dragged its feet on steam power and propellers in the first half of the nineteenth century; the army notoriously resisted new technology during the Civil War. Nor were rank-and-file scientists, jealous of their independence, anxious for close relations with the military. But the scientific leadership grasped the technological character of modern war and perceived that solutions to technological problems required not only engineering but also basic scientific research. During the Civil War they urgently lobbied for an agency to direct military research and development. The navy responded with a permanent commission that enjoyed civilian status, no funding, no research capabilities, no power, and little meaningful activity. The National Academy of Sciences (NAS), born in 1863, likewise contributed little to the war effort.

Much seemed the same when World War I began. In Europe and the United States the military misapprehended the character of technological warfare, but the stalemate rendered the military more receptive to new ideas. Fritz Haber convinced a skeptical German headquarters in 1915 to experiment with poison gas. A gas arms race ensued, which mobilized scientists on both sides; England's Porton Down occupied 7,000 acres, with a breeding colony for animal and human experimentation. Its scientists were better paid than those in other scientific occupations. In the United States, Edgewood Arsenal in Maryland, employing 2,000 people and turning out 200,000 bombs and shells per day, had no rival in size until the Manhattan Project.

The U.S. scientific leadership tried several approaches to mobilizing science for war. The Naval Consulting Board, Thomas Edison's child, applied methods of invention and engineering to problems of military technology and made little use of academic scientists. The National Research Council (NRC, a creation of the NAS) took a different approach, organizing basic research for war and uniting both academic and nonacademic scientists with engineers. Its leaders recognized not only what science could do for the war, but also what war could do for science.

By war's end, the NRC's success had demonstrated the need for fundamental scientific research in modern warfare. Academic science won greatly increased status. "Those who shared in the consciousness of the University's power and resourcefulness," remarked one dean, "can never be fully content to return to the old routine of the days before the war." Private foundations poured money into research projects. Industry, impressed with scientists' practical and managerial skills, welcomed them. The war introduced team-based research to American science, and, as it crippled European science, the war made the United States a world scientific power. But the military-scientific alliance was not perfect. The NRC could only coordinate projects; it had little money and could not contract out research. The military feared that academics would exploit its sponsorship for their own purposes. The National Advisory Committee on Aeronautics (NACA) offered a third, more promising approach to war-related research. Well funded and with authority to maintain its own laboratories, NACA forged strong ties among academics, government scientists, and the military. This model would shape the organization of science in the next war.

In 1941, the scientific rank and file again showed little interest in military work. Scientists who had served in World War I favored preparedness. Vannevar Bush had worked at the NRC's submarine detection facility and had served as chair of the NACA, as well as dean of engineering and vice president at the Massachusetts Institute for Technology (MIT), uniting, in his person, the historical precedents for a scientific-military alliance. Under his leadership the Office for Scientific Research and Development (OSRD) organized most scientific work for the war. Patterned after the NACA, the OSRD contracted out research and development to universities and industry, allowing scientists to work on military projects in civilian and academic settings. Huge projects at the nation's top universities and engineering schools—MIT's Radiation Laboratory employed 4,500, for instance—made essential contributions to the war effort. The Manhattan Project, an exception to this pattern, fell to the army under conditions that academic scientists were glad to escape at war's end.

World War II taught the nation that its security depended on technological superiority; that new military technology demanded fundamental research not tied to immediate needs; that big projects and lots of money produced great results; that the nation required scientists, who alone understood the new weapons, at the highest levels of strategic planning; and that an unfailing supply of them must be guaranteed through the cultivation of science education. These lessons shaped the institutional structure and the content of Cold War science. National laboratories at Argonne, Berkeley, Oak Ridge, Brookhaven, and later Livermore took up where the Manhattan Project left off, while universities and engineering schools carried on the approach of the OSRD. Wartime projects had built Stanford and MIT into great schools. Scientists from these and other select institutions favored by the OSRD had foreseen and jockeyed for greatly increased postwar support. Interdisciplinary departments in military-related fields like microwave electronics proved highly successful, as did quasi-independent laboratories managed by academic institutions, such as Johns Hopkins University's Applied Physics Laboratory and Charles Stark Draper's Instrumentation Laboratory at MIT. Besides microwave electronics, crucial to radar and communications, favored subject areas included materials science for semiconductor research, automated systems, and nuclear science.

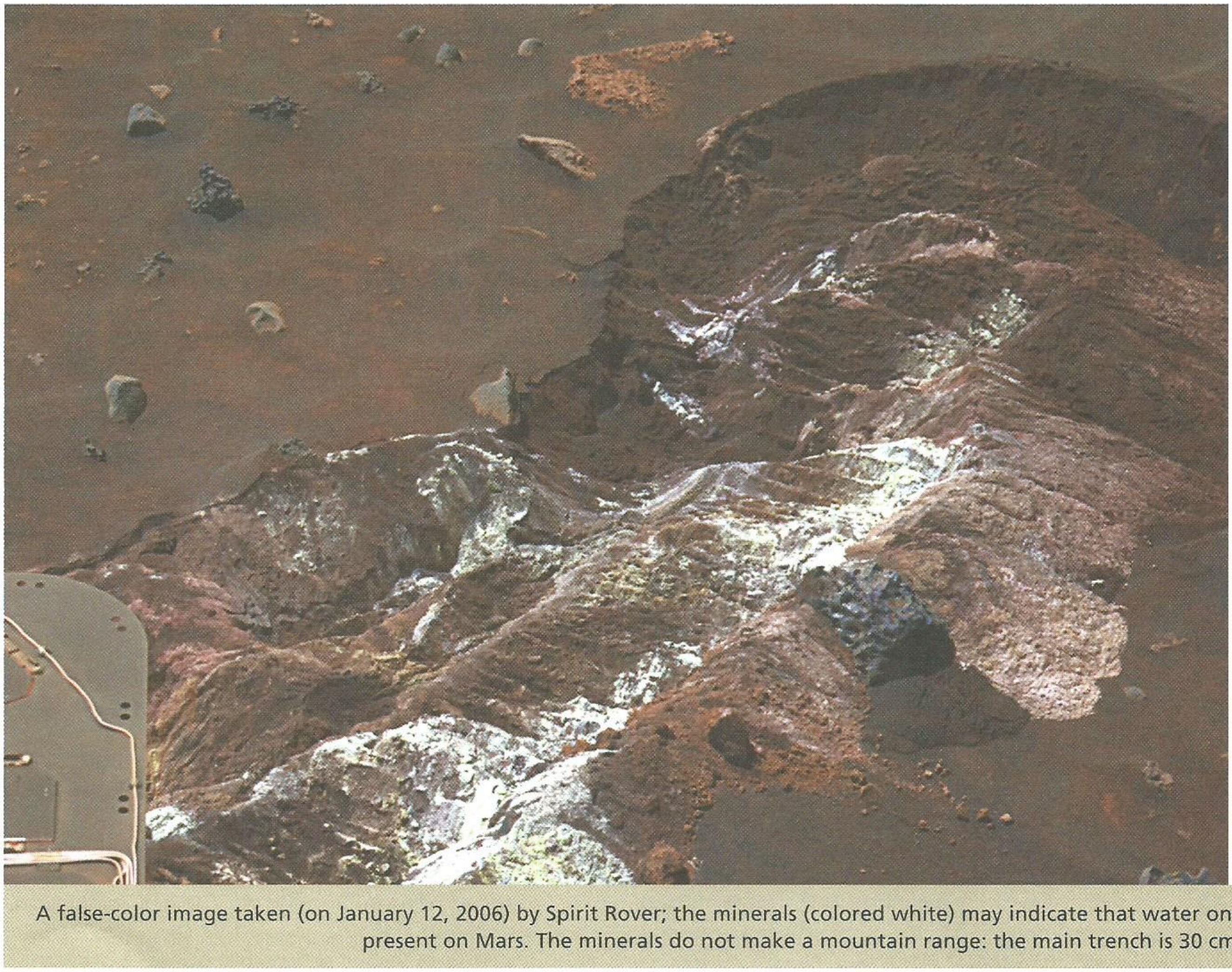
Through these institutions military relations helped to direct the orientation and shape the content of science. Military officers populated graduate programs, which in the immediate postwar years might include classified courses among their offerings. Graduate students wrote theses on military topics, then filled the ranks of the next cohort of professors. In subjects like quantum electrodynamics—the applications of which include lasers and semiconductors—theoretical approaches and results might respond to military requirements. Semi-military agencies like the RAND Corporation, applying the social sciences to military purposes, fostered pervasive quantification in these fields. The Korean War intensified the military influence in science. By late 1951, the Department of Defense and the Atomic Energy Commission (AEC) funded 40 percent of all academic and industrial research, while defense-related research occupied two-thirds of the nation's scientists and engineers. Through panels and summer study groups scientists advised the government on issues of technology and strategy. The General Advisory Committee to the AEC, for example, contributed to the decision to create the hydrogen bomb; it directly succeeded the Manhattan Project's Scientific Panel, which had advised the War Department on targeting and deployment of the atomic bomb. In all these ways American scientists helped the United States win the arms races of World War II and the Cold War.

THEODORE S. FELDMAN

MINERALOGY AND PETROLOGY. Mineralogy's disciplinary status has undergone three distinct shifts. From the sixteenth through the early nineteenth century, it bridged chemistry and natural history. It used the laboratory techniques of the former and the principles of classification of the latter to study the whole of the mineral kingdom. During the nineteenth century, mineralogy lost this commanding position and became a subdiscipline of geology. The study of minerals (chemicals that occur naturally in the earth's crust) separated from that of rocks (distinctive assemblages of minerals), leading to *a* distinction between mineralogy and petrology in the latter part of the century. Following World War II, geology came under the earth sciences, and mineralogy and petrology were transformed by the theory of plate tectonics and by new instrumentation.

In spite of changes in disciplinary status, from the eighteenth century to the present, mineralogists have concentrated on two problems. The first, classification, has been essential for geological theory and practical applications in mining. It has also been a scientific nightmare. Classifying depends on being able to make clear distinctions at various levels of organization. In the case of animals and plants, individuals can usually be distinguished easily and most of the time species too by the test of reproductive capability. Although in the eighteenth century, Carl Linnaeus made a gallant attempt to extend these methods to minerals, it was a doomed strategy. Over the centuries, mineralogists have oscillated between using chemical composition and crystal form. Unfortunately, these do not map onto each other. Two minerals of the same composition can have different forms, and vice versa. Adding to the difficulties, the chemical composition of many of the commonest minerals is not fixed but allows a range of variation. Formal classifications have always been supplemented by keys to field identification using a variety of visible characters.

The second key mineralogical problem is how minerals and rocks originated. Since they occur interlocked with one another, mineralogists from the seventeenth century on have assumed that they originated as fluids and subsequently hardened in their present positions. The fluidity could have been caused by heat, water, or some combination of the two. Mineralogists have fought recurrent battles over the relative importance of these factors. In either case, they have always hoped they would be able to use their knowledge of chemical reactions to reconstruct a genetic account of rock history—a geogony based on an invariable sequence of chemical reactions following from some initial state.



A false-color image taken (on January 12, 2006) by Spirit Rover; the minerals (colored white) may indicate that water once was present on Mars. The minerals do not make a mountain range: the main trench is 30 cm wide.

Mineralogy differed greatly from the historical geology better known to the public and more thoroughly studied by historians. Mineralogists have always focused their attention on the hard rocks (igneous and metamorphic). The sedimentary rocks so dear to historical geologists because of their embedded fossils have taken second place, even though mineralogists have attended to clay mineralogy and sedimentary petrology. Mineralogists have always worked closely with chemists and with crystallographers. They have found experiments and microscope work as important as fieldwork. Germans and Scandinavians dominated mineralogy partly because of the abundance of hard rocks in those countries, but also because of their distinguished traditions in chemistry and crystallography. Only in the twentieth century did they begin yielding to Canadians and Americans.

From the Renaissance through the eighteenth century, mineralogists produced one classification of rocks and minerals after another. Among the more important were Georg Bauer, better known as Agricola, the Swedish chemist Johan G. Wallerius, and Abraham Gottlob Werner. All distinguished four major groups with different chemistries: earths, metals, salts and combustibles. Earths resisted heat and water, metals became fluid on heating, salts dissolved in liquids, and the combustible substances (coal, for example) burned. Because chemistry formed the basis for classifying rocks, the students spent as much time in the cabinet or laboratory working with chemicals and blowpipes as they did in the field. Werner drew the pessimistic conclusion that no theoretically sound principles of mineral classification were to be found. Hence he instructed his students to begin dividing up rocks by the time of their formation.

Employed by European states as mining inspectors or surveyors, mineralogists left their laboratories to climb mountains and descend mine shafts. By the second half of the eighteenth century, these men—including Lazzaro Moro and Giovanni Arduino in Italy, Johann Lehmann in Germany, and Guillaume-François Rouelle in France—opted for an alternative approach to rock classification. They divided rocks into two main kinds: primary and secondary. Primary rocks were hard, often crystalline and the matrix in which metals and precious minerals were to be found. They made up the core of mountain chains. Secondary rocks were relatively soft and granular, layered or stratified and banked up against the primary rocks that formed the mountain cores. Often, secondary rocks contained fossils, which by then most mineralogists agreed were the indurated remains of animals and plants.

In seeking the causes for this twofold division of rocks, mineralogists found common ground with cosmogony, the study of the development of the globe. Since the seventeenth century, cosmogonists had argued from the earth's globular figure that at some time in the past it had been fluid. Fluidity could have been caused by heat, as a minority of cosmogonists had argued. Mineralogists, though, preferred water, as suggested by the chemist Johann Joachim Becher in his *Physica subterranea* (1669). They believed that a thick, chemical laden ocean had once covered the earth's surface. The primary rocks crystallized out of the ocean as the high mountain chains, a conclusion supported by the chemists' belief that crystals could be deposited only from watery solutions and not from hot melts. As the water became less saturated, and as waves and rivers wore away the mountains, the ocean began depositing the silt that solidified as the secondary, stratified rocks. This theory, Neptunism, was most fully developed by Werner at Freiberg.

From about 1830 to 1880, mineralogists looked to new developments in chemistry to aid them with mineral classifications. Jöns Jacob Berzelius, the Swedish chemist, distinguished the silicates and aluminates—the classes of chemicals most abundant in the earth's crust for the first time. Gustav Rose offered the most comprehensive classification of minerals to date in his *Mineralsystem* (1852). For practical purposes, mineralogists continued to use external features. Friedrich Mohs, best known for developing a hardness scale for minerals, developed one of these. James Dwight Dana adapted it for an American audience. His *System of Mineralogy* published in 1837 must be one of the most enduring of textbooks in the history of modern science. In modified form, it was still in use in the 1960s.

In 1860, Henry Clifton Sorby invented the polarizing microscope, transforming the process of identifying minerals. Thin sections of minerals or rocks were placed on slides that could be rotated beneath polarizing lens. The characteristic color changes that were observed on rotating the slide served to identify the mineral. This new technique allowed mineralogists for the first time to see and identify mineral assemblages formerly invisible to the naked eye. It gave an enormous boost to petrology. Karl Rosenbusch used it to particularly good effect, summarizing the new results in his classic textbook, *Mikroskopische Physiographie der petrographisch wichtigen Mineralien* (1873).

In the nineteenth century, theories of the origin of rocks and minerals also became more sophisticated. Charles Lyell suggested that besides volcanic, plutonic, and sedimentary rocks, geologists needed a fourth category, which he called metamorphic. These arose through transformation of the other classes by heat and pressure. While agreeing that gneisses, schists, and perhaps granite might be problematic, continental mineralogists continued to believe that water, perhaps under heat and pressure, perhaps containing many strong chemicals, was crucial to petrographic change. Carl Gustav Christoph Bischof summed up the state of the argument in what became the standard geochemical text, *Lehrbuch der chemischen and physikalischen Geologie* (1848). In Canada, Thomas Sterry Hunt made another stab at a chemical geogony. His theory was rejected.

At the end of the nineteenth century, mineralogists and petrologists found that new research in thermodynamics, particularly that of J. Willard Gibbs on the phase rule, offered an alternative way to think about mineral and rock origins. They began constructing phase diagrams for certain common rocks to clarify the sequence and manner in which the different crystals had formed. The founding of the Carnegie Institute of Washington in 1902, and the construction of a lavishly equipped laboratory there, aided this program of research. The United States could now compete with Germany. In 1928, Norman Bowen summed up then recent developments in his classic, *The Evolution of the Igneous Rocks* (1928).

The question of the origin of the rocks was pursued in the field as well as in the laboratory by two opposing camps that frequently compared themselves to the Neptunists and Plutonists of a century earlier. The minority camp, the migmatists, believed that migmatites (as they called the puzzling hard rocks of varied composition) were formed in place as circulating fluids converted extant rocks into something completely different. The majority camp, the magmatists, led by the Canadians Norman Bowen at the Carnegie Institute and Reginald Daly at Harvard, argued that they were intruded from reservoirs of molten magma beneath the earth's crust.

Within this camp, heated debates raged about whether there was one magma or many, and whether magmas were homogenous or differentiated. There the matter stood at the beginning of World War II. Following the war, novel techniques in the laboratory and the field, including deep sea drilling, suggested new directions for mineralogical research.

RACHEL LAUDAN

MOHOLE PROJECT AND MOHOROVIČIĆ DISCONTINUITY. The purpose of the Mohole Project (1957–1966) was to drill through the earth's crust to the Mohorovičić discontinuity, the seismic interface between the earth's crust and mantle. This boundary was discovered in 1909 by Yugoslav geophysicist Andrija Mohorovičić who noted that seismic waves returning from depth indicated there was a zone of abrupt change in the speed of seismic waves some kilometers below the earth's surface. Called Moho for short, this zone defines the base of the earth's crust and marks a change in composition. The depth of Moho varies from about 25–40 km (15–25 mi) beneath the continents, to 5–10 km (3–6 mi) beneath the ocean floor. Recently, following the acceptance of plate tectonic theory, geoscientists have decided that changes in deformational behavior are a more significant aspect of the earth's structure than changes in composition. They divide the outer earth into the rigid lithosphere (crust and upper mantle) overlying the more deformable asthenosphere.

Project Mohole was the brainchild of AMSOC, the American Miscellaneous Society, an informal group of geoscientists formed in the 1950s. Prior to this, crustal drilling was primarily undertaken to explore for oil and gas and had been limited to land and shallow water. Drilling for scientific purposes was much less common. It had begun with efforts to determine the structure, composition, and history of coral islands. In 1877, the Royal Society of London sponsored a borehole that went down 350 m (1,140 ft) on Funafuti in the South Pacific. In 1947, pre-bomb-test drilling of Bikini reached 780 m (2,556 ft). In 1952, drilling on Eniwetak finally reached basaltic crust beneath coralline rock at a depth of over 1,200 m (4,000 ft), still well short of the Moho. In the 1950s, some countries, including Canada and the Soviet Union, proposed drilling deep holes in continental crust.

Project Mohole, funded by the U.S. National Science Foundation, was designed to drill in the deep sea. The technological challenge was to drill the deep-ocean floor in water depths of thousands of meters. Although Mohole successfully drilled cores in water depths of 950 and 3,560 m (3,111 and 11,672 ft), it did not come close to reaching the Moho. Mohole, commonly seen as one of the first big-science projects in the United States, was terminated by Congress in 1966 and widely considered to have been a failure.

Nonetheless the project demonstrated that ship-based ocean drilling was feasible. It helped spawn the highly successful Deep Sea Drilling Project, begun in 1968, to drill through cover sediments on the ocean floor. Since then scientific deep-ocean drilling has become an international endeavor. Oil companies are reaching deeper and deeper objectives. Moreover, a number of countries and consortia have developed continental deep-drilling projects. None of this drilling has reached the Mohorovičić discontinuity, however.

Even so, scientists now believe that we can observe the Moho on land. By the late nineteenth century, a number of European scientists had recognized that in the Alps uplifted oceanic crust was represented by layered chert (lithified deep-sea sediments) overlying basalt (oceanic crust) overlying ultramafic rocks (high-density rocks rich in iron and magnesium), the so-called Steinmann trinity, after Gustav Steinmann. This package of rocks is called an ophiolite, and the transition from basalt to ultramafic rocks is believed to be the crust-mantle boundary—the Mohorovicic discontinuity.

JOANNE BOURGEOIS

MOLECULAR BIOLOGY. The second half of the twentieth century witnessed a transformation in our understanding of certain key mechanisms fundamental to life. These mechanisms concern the biological phenomena of heredity and development and the chemical processes of the synthesis of proteins and nucleic acids. The techniques developed to investigate these phenomena and the conceptual structure into which they have been fitted constitute the subject known as molecular biology. The former can be likened to a toolkit and the latter to a manual. They have been put to work in numerous areas of biology from phylogeny and population genetics to immunology and neuroscience. With advances in these techniques have come applications to pharmacology (designer drugs), in agriculture (recombinant strains of crop plants), and in forensic science (DNA fingerprinting).

More than a toolkit and manual, molecular biology represents a combination of approaches of the chemist, biochemist, geneticist, and microbiologist, and offers a unifying conceptual structure provided by the mechanism and genetic determinants of protein synthesis. It can hardly be called a discipline, however, because its techniques have been absorbed by biochemists and geneticists, by embryologists, immunologists, and ecologists, and their disciplines have not blended. The practice of molecular biological techniques in so many areas of biology has made it a common currency in the many areas of the science of life.

Since all living things are constituted of molecules, and biochemists have always studied the behavior of molecules, why has molecular biology stirred up so much adverse comment? As Erwin Chargaff once quipped, a molecular biologist is a biochemist practicing without a license. Molecular biology is interdisciplinary to an extent that biochemistry never was before biochemists faced those who were to call themselves molecular biologists. The approach of the biochemists, dominated by their concern to unravel the nature of metabolism, its pathways and energetics, rarely included genetics, and paid only occasional attention to structural crystallography. And among chemists, those studying natural products concentrated on the proteins and the carbohydrates, leaving the nucleic acids to a mere handful of researchers. The change in biochemistry came when scientists accepted the notion that the genetic material consists of nucleic acid, not protein, and that the nature of a protein depends on the nature of the nucleic acid in the presence of which it is formed.

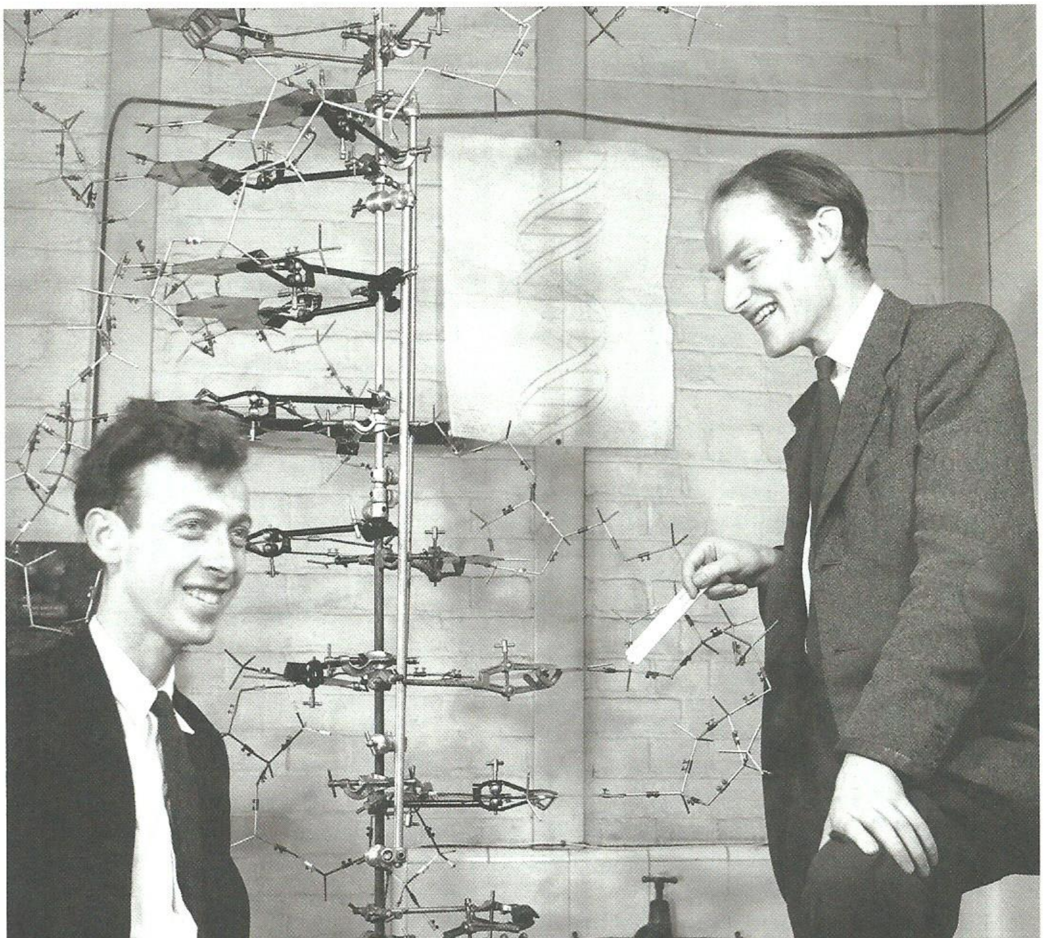
But again, had not biophysics a long history before 1950? Biophysicists had been very active in the study of the nerve impulse, the behavior of membranes, and the effects of ionizing radiations, and, in conjunction with physical chemists, they had investigated large molecules by ultracentrifugation and electrophoresis. But as a group, biophysicists concentrated on technique and did not immerse themselves in the conceptual problems of biology. Thus, when deoxyribonucleic acid (DNA) rose to prominence as the stuff of the genes, those involved gave their work a new title to distinguish it from that of the biochemists and biophysicists around them. This they achieved through such instruments as the *The*

Journal of Molecular Biology published by Academic Press beginning in 1959, the renaming of the Medical Research Council Unit for the study of the Molecular Structure of Biological Systems in Cambridge as the MRC Laboratory of Molecular Biology (1956), and the publication of James D. Watson's *The Molecular Biology of the Gene* (1965).

The Festschrift to the German physicist-turned-biologist, Max Delbrück, *Phage and the Origins of Molecular Biology* (1967), pointed to the work of the group formed around Delbrück to study the process of replication in bacterial viruses as the source of molecular biology. This book provoked a response from John Kendrew in *Scientific American* pointing out that the phage group was one source, but not the only one. Structural X-ray crystallography of the proteins was the other. He dubbed the former the "Informational School" and the latter the "Structural School," using the term school in a loose sense to refer to a network of researchers who, though scattered, constitute specialist communities. By the time Watson's enormously influential fragment of autobiography, *The Double Helix,* appeared in 1968, the three elements—phage, structural chemistry, and the addition of physics to biology—had become the distinguishing features of the popular history of molecular biology.

This historiography has been criticized. The salience given to the physicists, it is argued, exemplifies the construction of history by the actors to legitimize their importance. True, the search for a parallel to the physicists' complementarity principle in biology led nowhere, and the solution to the mysteries of the gene—how it duplicates, maintains its constancy, mutates, and is expressed—came from a combination of chemistry, genetics, and cytology, not physics. But indirectly, physics informed the disciplines of X-ray crystallography and physical chemistry by establishing the nature of the chemical bond, and offered a model in Delbrück's career for collaborative research among the phage workers. Also, physicists helped with funding; for example, Sir John Randall used the influential position he had gained for his war work to mastermind the establishment of the first research unit of the UK's MRC given to the biophysical study of the cell. Revisionist histories also complain that too much emphasis has been placed on the influence of the Austrian physicist Erwin Schrödinger's book, *What Is Life?* (1944) in drawing physicists and chemists to biology; but it is difficult not to accept the testimony of Francis Crick and Maurice Wilkins who were inspired by the eloquent appeal of *What Is Life?* to explore the remarkable properties of the gene, which, like an aperiodic crystal, so faithfully replicates its structure.

The conceptual structure that constitutes molecular biology consists first of the assertion that proteins arise through an interaction between certain proteins and certain nucleic acids. They owe their shape, long held to determine their specificity, to the folding of the long polypeptide chains that compose them. The manner of folding is determined by the specific sequence of the building blocks or "residues" (amino acids) along the chains, not, as formerly suggested, by the presence of another molecule to which they adopt a complementary shape. The sequence does not arise, as many had assumed, from the sequential action of a battery of proteolytic enzymes, but to the sequence of residues or bases on the polynucleotide chain of a nucleic acid (DNA) in the cell's nucleus acting as a template. The sequence represents a code or cipher for the amino acids of the protein being synthesized. It is copied from the DNA of the chromosome in the nucleus onto a "messenger" ribonucleic acid (mRNA). Passing out into the cytoplasm, the mRNA determines the sequence of amino acids in the protein being synthesized. DNA makes RNA make protein.



James Watson (b. 1928) and Francis Crick (1916–2004), with their model of the structure of DNA they worked out in 1953

In 1957, Crick codified this picture in an address to biologists entitled "On Protein Synthesis." He stated two general principles: *the sequence hypothesis,* "the specificity of a piece of nucleic acid is expressed solely by the sequence of its bases . . . this sequence is a (simple) code for the amino acid sequence of a particular protein," and the *central dogma,* "once information has passed into protein *it cannot get out again* . . . the transfer of information from nucleic acid to protein may be possible, but transfer from protein to protein, or from protein to nucleic acid is impossible" (Crick, 1958). Crick defined carefully his use of the term "information": "the *precise* determination of sequence, either of bases in the nucleic acid or of amino acid residues in the protein." This understanding of the term implied a functional meaning in contrast to the purely syntactic meaning found in information theory.

In the decade following Crick's address, molecular biologists addressed the major features of protein synthesis and discovered all parts of the code relating nucleic acid and protein sequences. A sense of triumph marked the completion of this first phase of molecular biology extending from the 1950s to the mid-1960s. The emerging picture was simple. The information in DNA determines the information in the proteins according to a universal code. Since all that remained was filling in the details, many of the leaders among the molecular biologists began to look elsewhere for fresh problems to solve. Those who stayed the course engaged in a surprising and revealing task.

Exceptions were soon reported, both real and apparent, to the universality of the genetic code, to the sequence hypothesis, and to the central dogma. The concept of the gene, once unambiguous, became a term with multiple meanings as molecular tools dissected it in varied ways. With the introduction of the techniques of recombinant DNA in the 1970s came novel methods to manipulate the genetic material and to reveal the multiple levels of control of gene expression possessed by the cell. The discovery in 1970 of enzymes (reverse transcriptases) that copy RNA base sequences back into DNA upset the complacent assumption that information only flows from DNA to RNA—a direction allowed for in Crick's statement of the *central dogma,* but widely assumed not to be possible. The revelation in 1977 that often only parts of the message (mRNA) from the DNA is translated into protein destroyed the simple one-to-one relationship between a DNA sequence and a polypeptide chain. Other discoveries revealed that much of the chromosomal DNA of higher organisms does not carry the information to determine a given polypeptide chain, but has some other function, gene regulation being one.

This second phase of molecular biology lasted from the 1970s to the present. In several respects it is a transformed version of the first phase. In the past, critics accused molecular biologists of adopting a too-reductionist approach, but the multi-level picture of the system of gene expression that has emerged in the second phase of the subject makes this accusation hard to justify. The most significant intellectual outcomes of the current phase of the subject relate to evolution and development. On the one hand, the extent to which the molecular machinery of the cell has been conserved in evolution has surprised everyone. On the other, the attribution of so much of biological diversity to the variety of ways in which the same genetic equipment is expressed has directed increasing attention to the genetic control of development. The recent success in sequencing the human genome, and those of several model organisms, has strikingly emphasized these points.

This more sophisticated molecular biological science has in the last three decades of the twentieth century been put to work in many fields, in none more dramatically than embryology. By 1980, all knowledgeable people recognized that the tools of recombinant DNA technology were opening up methods for the manipulation of genetic material of considerable commercial promise to industry. With these techniques, organisms and their products could be designed for specific purposes. No longer did humans have to wait for nature to turn up the right genetic combination through long, continued breeding. Parasexual processes came to complement or replace sexual processes and to bridge the chasm separating genera. Such power to produce trans-genic organisms has led to accusations that molecular biologists are "playing God" and endangering nature. The development in 1985 of the polymerase chain reaction (PCR) has made possible the amplification of minute quantities of DNA—even a single copy—a technique of great versatility for medicine and science. Thus, from an esoteric exploration of the nature of the gene, its message, and its product, molecular biology has moved into the marketplace, and now plays *a* significant part in the economic and social culture of the twenty-first century.

Robert Olby

MULTINATIONAL LABORATORIES. During the Cold War, few nations outside the two superpowers had the resources to drive big science. Countries wishing to compete with them had to pool resources. The pooling worked particularly well in Europe and in the physical sciences. Reconstruction requirements, Cold War dilemmas, the threat of Stalinism, competition from the United States, support from international organizations, and an understanding of limitations combined with the politics of European unification to provide the setting for the emergence of European multinational laboratories. The Soviet bloc and other regions also housed multinational projects, which remained, however, under national control.

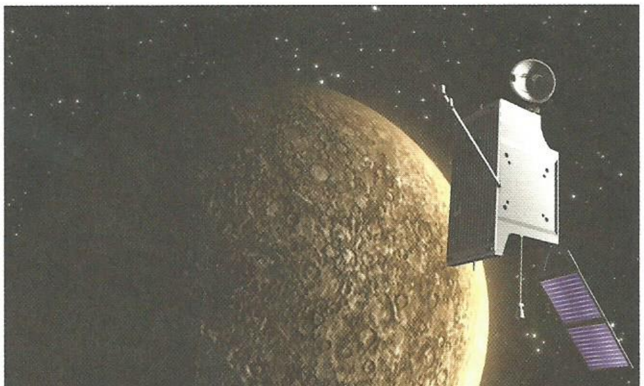
Several overarching political institutions assisted the development of European multinational laboratories: the Organization for European Economic Cooperation (OEEC) formed in April 1948 to manage the Marshall Plan and transformed in 1960 into the Organization for Economic Cooperation and Development (OECD); the North Atlantic Treaty Organization (NATO), created in April 1949; and the European Coal and Steel Community (ECSC), agreed to by France, the Federal Republic of Germany, Belgium, the Netherlands, Luxembourg, and Italy in April 1951. In 1957, Belgium, France, the Federal Republic of Germany, Italy, Luxembourg, and the Netherlands signed treaties setting up the European Economic Community (EEC) and European Atomic Energy Community (EURATOM), both of which merged with the ECSC in 1967. The High Authority established to supervise the ECSC treaty became the European Commission. The EEC made explicit its European Community Research, Technology, and Development policy in 1974, the same year that the first elections to the European Parliament were held. The first laboratory created within this broad political context was the European Organization for Nuclear Research (CERN), which gained broad support.

Louis de Broglie issued the first high-level call for a multinational laboratory as an instrument to revive Euro-

Louis de Broglie (1892–1987), French physicist, the prime mover in the invention of wave mechanics, and, though he almost never left France, a proponent of international laboratories.

pean science at the Lausanne European Cultural Conference in 1949. Supporters of the call included Raoul Dautry, administrator-general of the French Atomic Energy Commission; Pierre Auger, director of UNESCO's Department of Exact and Natural Sciences from 1948 to 1959; and Edoardo Amaldi, one of the founders of Italy's National Institute for Nuclear Physics. UNESCO provided the institutional framework for CERN. In 1951, Cornelis Jan Bakker and other UNESCO consultants presented their recommendations. They called for a temporary organization, $200,000 in funding, and eighteen months to prepare an administrative, financial, and technical program.

Niels Bohr offered his institute as a home for CERN; the offer was accepted, but only for the theoretical group. The representatives of the eleven countries that set up CERN in February 1952 chose Amaldi as secretary general of the new laboratory, and in October decided to build it near Geneva. The formal founding of CERN by the Federal Republic of Germany, Belgium, Denmark, France, Greece, Italy, Norway, the Netherlands, the United Kingdom, Sweden, Switzerland, and Yugoslavia took place in 1954. In October 1954, Felix Bloch succeeded Amaldi and became CERN's first permanent director general. Though motivated by American competition, the CERN management did not reject Ford Foundation funding. The Soviet inauguration of the Dubna 10 GeV protonsynchrotron in 1957 introduced a second major competitor. CERN's first accelerator, a 600 MeV proton synchrocyclotron, was inaugurated in 1957, coordinated by Bakker. The CERN proton-synchrotron, whose development was led by Odd Dahl, began operating in November 1959 at 28 GeV.



The BepiColombo Mercury Planetary Orbiter of the European Space Agency

Nearly half of the particle physicists in the world work at CERN, supported by a staff of three thousand. The size of the operation and the number of researchers complicate relations among project managers. Traditional European disciplinary divisions created more problems than did nationa differences. In contrast to the American tradition, CERN at first kept science apart from engineering and performed poorly in comparison to the Brookhaven laboratory. European scientists had to learn how to do big science.

Good management and a research focus on reproducible results raised CERN gradually from an institution that missed opportunities in the 1960s and that still had a low reputation in the mid-1970s, to the renowned producer of W and Z boson results and Nobel Prizes.

The failure to establish CERN in Copenhagen—the theoretical group moved out in 1957—motivated the creation in its place of the Nordisk Institut for Theoretisk Atomfysik (Nordita). Bohr and his colleagues recognized that none of the Nordic countries alone commanded sufficient resources to compete in nuclear and elementary particle physics—despite the Norwegians' success in operating JEEP, the first nuclear reactor outside the sphere of the major powers in 1951. Moreover, experience with the UNAEC revealed some of the barriers that the Cold War introduced into nuclear science.

In January 1953, Bohr from Denmark, Torsten Gustafson from Sweden, and Egil Hylleraas from Norway met at Gothenburg to organize an atomic committee. The timing was politically appropriate: the following month, the Nordic Council had its first meeting in Copenhagen. Finland joined the Nordita project in November 1955 and Iceland in January 1956. Bohr gained the Nordic Council's approval for Nordita in February 1957. Nordita started operations on 1 September 1957, within a month of the departure of CERN's theoretical group from Copenhagen.

In the same year, EURATOM set up its Joint Research Center (JRC) at Ispra, near Lago Maggiore in the north of Italy. Centers at Karlsruhe (1960), Geel (1961), and Petten (1961) followed. Until 1973 JRC focused on nuclear energy. After that, it diversified into other fields. During its first decade EURATOM hesitated over its goals, which made the management of the JRC very difficult. Should it be an instrument for industrial or energy policy, or a nuclear research organization? JRC's functions varied from selling nuclear energy to advocating its peaceful uses.

The U.S. Atoms for Peace policy had motivated the creation of EURATOM; Europeans wanted nuclear independence. The Germans had experienced U.S. restrictions since an American intervention had stopped a joint project with Brazil in the early 1950s. The French supported EURATOM and the JRC only on condition that they could develop nuclear weapons. Nothing in the EURATOM charter appeared to prevent it. EURATOM also permitted the free movement of nuclear raw materials.

The JRC employed the concept of the five-year research program now a cornerstone of the European Commission's research policy. The first program, 1958–1962, divided the tasks into in-house or direct research and external contracts or indirect research. In 1959, thanks to Francesco Giordani, head of the Italian National Research Council, the nuclear research center at Ispra was transferred to EURATOM. The second program, 1963–1967, continued this trend, putting more weight on direct research.

A crisis ensued in 1968, when it became clear that EURATOM did not synchronize with national programs. A European atomic consensus did not exist. Most of EURATOM's projects stagnated or stopped, notable exceptions being the biological program and the fusion research project, the Joint European Torus (JET). The crisis was linked to tensions between Great Britain and France. The JET lab ended up near London.

Support for the JRC returned once it became clear that a growing scientific gap existed between Europe and America, and that European scientists were emigrating to the United States. In 1974, the Europeans decided on a common science and technology policy and chose in 1977 six areas of action for the JRC: energy; raw materials; environment; living and working conditions; the network for the exchange of technical information (Euronet); information science, telecommunications, and transport. The JRC became a research infrastructure for these areas. In December 1982 the European Strategic Program for Research and Development in Information Technology (ESPRIT) was approved. It engaged European information technology industry in JRC projects.

The reorganization of the JRC in 1988 brought further diversification: a headquarters in Brussels, the Institute for Reference Materials and Measurements (IRMM) in Geel, the Institute for Transuranium Elements (ITU) in Karlsruhe, the Institute for Advanced Materials (IAM) in Petten, the Institute for Systems, Informatics and Safety (ISIS), the Environment Institute (EI), the Space Applications Institute (SAI), and the Institute for Health and Consumer Protection (IHCP) in Ispra, and the Institute for Prospective Technological Studies (IPTS) in Seville. The JRC acquired a staff of nearly 2,500, of which 1,600 were researchers. After 1998, the JRC became not only the scientific and technical support for implementation of the European Union's policies but also its reference center for science and technology. Nearly 30 percent of the JRC's total budget of approximately 300 million euros now goes to nuclear activities. The JRC competes increasingly for funding from private as well as public sources.

Another important European multinational science institution is the European Space Agency (ESA). Again a unifying theme facilitated the alliances between scientists. ESA evolved from the European Space Research Organization (ESRO) and the European Launcher Development Organization (ELDO), which had confronted gigantic political and economic difficulties. As at CERN, Auger was a central figure. His years, from 1959 to 1967, were learning years. But they were also years when several European countries tried to develop their own space programs. Under Auger's inspiration, ESRO and ELDO achieved some successes, for instance launching fifty-six sounding rockets, but fell short of expectations.

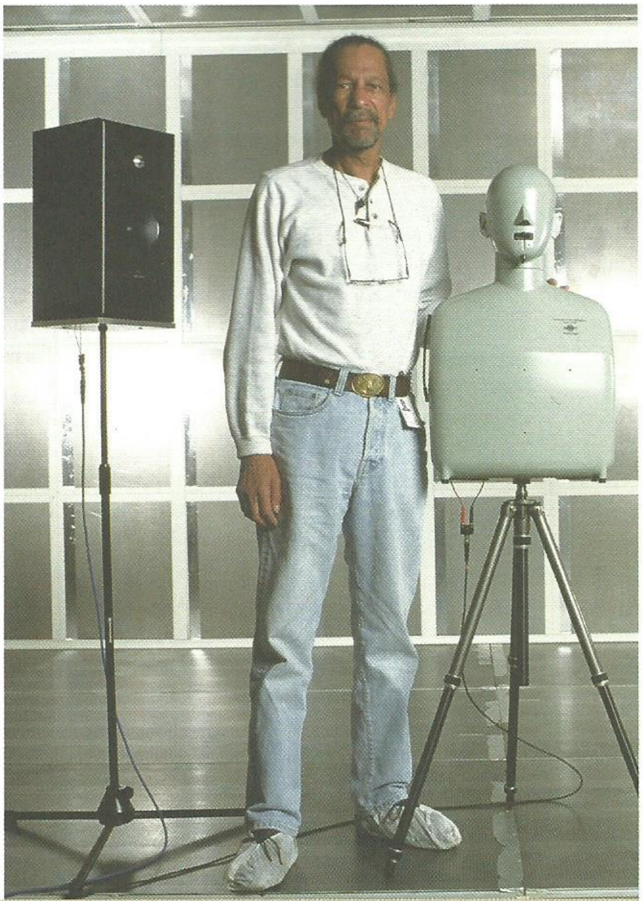
From 1969 to 1973, under Hermann Bondi, ESRO evolved into ESA. Research fields comprised fundamental physics, plasma physics, high-energy X-ray and gamma-ray astrophysics, and special cosmic-ray studies and measurements of solar neutrons and charged particles. The Bondi era began optimistically, but the agency soon confronted the realities of costs and the need to accept cooperation with the Americans and the Soviets. Cooperation collapsed under the strains of the Skylab project, forcing a search for alternatives. The deployment of Ariane in December 1979 gave the Europeans autonomy. Despite substantial scientific achievements, ESA's budget is no larger than ESRO's in real terms. ESA has achieved cooperation (and competition) with the United States on equal terms, which none of the European nations alone could have done.

There is a difference between integrated and interdependent multinational organizations. An integrated laboratory like the JRC has a supranational organization behind it, like the ECSC treaty of 1951 and the EEC treaty of 1957. CERN does not have such a structure and, therefore, its members have an interdependent relationship. That the JRC carried the main burden of integration may have allowed CERN the institutional space to pursue pure science. Historians of science have not yet evaluated the contributions of key JRC actors such as David Wilkinson, Marc Cuypers, and, especially, Hans Jörgen Helms, a former JRC director and one of the key institutional builders of European science. Indeed, the history of European big science in general has yet to receive the attention it deserves. When the overdue examination comes, it will find a clear temporal marker: in a single year, 1957, Nordita started operations, CERN's synchrocyclotron came on line, the JRC was created and, on the other side of the Berlin wall, the first *Sputnik* flew.

Regis Cabral

MUSIC AND SCIENCE. In the early twenty-first century, the relationship between science and music is typically understood in terms of particular specialties within the natural and human sciences (e.g., architectural acoustics, the physics of musical instruments, neurosciences), and what these can reveal about music's physical and cognitive effects. A longer historical perspective, however, shows that the disciplines of both science and music have altered dramatically over the last few hundred years. New technologies have transformed musical as well as scientific practice, and through their use of instruments and shared understanding of measure and time, the two domains have been closely intertwined. Before Isaac Newton transformed the mathematics of physics, the paradigm was "nature is musical"; thereafter the formula became "music is natural."

Since the Enlightenment music has been classified among the fine and performing arts; consequently, its role in the Scientific Revolution of the seventeenth century has generally been overlooked. Until around 1700, however, music was considered to be a science as well as an art, that is, a body of systematic theory including both practical and speculative aspects. It was also an academic discipline: music, astronomy,



American acoustic engineer James Edward West (b. 1931) in his laboratory at Bell Labs. West is perhaps best known for his microphones.

geometry, and arithmetic made up the mathematical sciences of the quadrivium, which, together with the trivium (grammar, rhetoric, and logic), formed the core of the medieval arts degree course. Up to the sixteenth century the most authoritative source on musical science was Boethius's *De musica* (sixth century A.D.), which promoted the Pythagorean harmonic doctrine that audible music is a tangible expression of the underlying mathematical principles (harmonia) governing the relations between the elements of all significant structures in the cosmos.

Some musicians were already declaring this harmonic tradition irrelevant to their art in the early sixteenth century. Practitioners who played instruments with fixed pitches like keyboard and lutes realized that polyphonic music composed for two or more parts did not agree with the Pythagorean scale defined by the ratios of small integers. This conflict between musical practice and theory played a significant part in the emergence of experimental science as the physical properties of musical instruments, especially the vibration of strings, increasingly became the subject of philosophical enquiry. In his *Istitutioni harmoniche* (1558), the Venetian composer and music theorist Gioseffo Zarlino presented a new theory of consonance, which he claimed had been tested experimentally. The lutenist Vincenzio Galilei disputed Zarlino's scenario, and in the process became the first person to check the results of Pythagoras's legendary experiments with hammers, strings, and other sounding bodies. He proved that most of them were wrong. Galileo Galilei—an accomplished lutenist like his father—further investigated the properties of vibrating strings and announced his findings in the *Discourses Concerning Two New Sciences* (1638). Although Galileo understood the relationship between pitch and frequency, credit for the discovery of the physical variables governing the pitch of musical strings goes to Marin Mersenne, whose *Harmonie universelle* (1636) contained the first published account of "Mersenne's laws." These boil down to the formula that frequency is proportional to the square root of string tension, and inversely proportional to string length as well as to the square root of the string's thickness.

The universal harmony of Mersenne's title indicates that although musicians rejected Pythagorean intonation on empirical grounds, early modern mathematicians continued to find the tradition of speculative harmonics inspiring. Johannes Kepler saw his search for universal mathematical laws as an extension of Ptolemy's *Harmonics* (second century A.D.), which assumes that sounding music *(musica instrumentalis)* embodies the harmonic principles governing human and also cosmic bodies *(musica humana et mundana)*. Kepler's *Harmonices mundi* (1619) builds on the concept that God created the world in accordance with geometric archetypes reflecting musical consonances. Kepler calculated the "harmony of the spheres" derived from the maximum and minimum angular velocities of the planets measured from the sun. The musical ratios that express these intervals are not Pythagorean, however, but those shown by Zarlino to be the basis of modern polyphonic practice.

The relationship between music and science thus developed in two complementary directions during the seventeenth century. First, musical phenomena continued to be investigated in their own right, most notably in the new field of acoustics. Joseph Sauveur claimed to have established this discipline in 1701, but Francis Bacon had already identified the "Acoustique Art" in his *Advancement of Learning* (1605) as exemplifying his new scientific method. Mersenne's systematic investigation of the properties of musical sound was taken up in the Royal Society of London and the Paris Académie Royale des Sciences. At the same time, however, musical/harmonic models continued to be fruitfully applied to other branches of the physical sciences. Robert Hooke, for example, postulated a unified theory of matter in which all particles act like musical strings vibrating sympathetically. Mersenne's laws similarly provided Newton with the basis for his analogy between colors and musical tones in the *Opticks* (1704), as well as his wave theory of sounds presented in the *Principia mathematica* (1687).

The success of the Newtonian synthesis brought the study of the relationship between music and science during the eighteenth century almost entirely within the framework of mechanics. In his *Traité de l'harmonie* (1722) the composer and theorist Jean-Philippe Rameau reduced the rules of harmony to a single principle of fundamental bass, which he compared to Newton's gravitational laws. Musical phenomena such as resonance and the overtone series appeared in popular texts of experimental physics, and were a staple of lecture demonstrations of natural philosophy. Meanwhile, leading European mathematicians like Jean Le Rond d'Alembert, Daniel Bernoulli, and Leonhard Euler disputed the mathematics of vibrating strings, a debate that contributed to the development of a viable theory of sound propagation. Pierre-Simon de Laplace's employment of the caloric theory of heat to resolve discrepancies between calculated and observed velocities of sound was a centerpiece of the physical science of the early eighteenth century. Enlightenment medical theorists also sought to explain music's effects in terms of vibration. Richard Browne's *Medicina musica;*

or, A Mechanical Essay on the Effects of Music, Singing and Dancing (1729) was one of the earliest treatises to address the physiological and psychological mechanisms governing human responses to music.

The nineteenth century marked a new, instrumental phase, which coincided with the shift to laboratory science as the dominant model of scientific practice. Ernst Chaldini's *Die Akustik* (1802) showed that most complex musical phenomena could not be explained by prevailing theory. Charles Wheatstone, Félix Savart, and other nineteenth-century physicists relied on new acoustical instruments (tonometer, siren, resonator, kaleidophone, speaking machine, etc.) in their quest to analyze and synthesize musical sounds and human speech. These acoustical experiments had important consequences for the scientific analysis of music. They provided the essential background for *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (1863), in which Hermann von Helmoltz established his new discipline of physiological acoustics. They also contributed to the invention of Alexander Graham Bell's telephone (1876) and Thomas Edison's phonograph (1877), technologies where parallel research into acoustical and electromagnetic phenomena converged for the first time. These inventions signaled a long-term shift from mechanical to electrical forms of sound production. In the short term, they had immediate application in the emerging field of psychological acoustics. Wilhelm Wundt and Carl Stumpf investigated the perception and judgment of musical tones, while Lord Rayleigh, whose *Theory of Sound* (1877) set the research agenda for the next fifty years, consolidated Hermann von Helmholtz's advances in physical acoustics. On the basis of Rayleigh's work and new materials for the absorption of sound, the Harvard physicist Wallace Sabine developed a new applied science of architectural acoustics.

During the twentieth century, the ability to record and reproduce sounds electronically had an enormous impact on the production and consumption of music. For the first time (except for barrel organs and other musical automata) it became possible to hear music without requiring live musicians. The music industry expanded in the wake of demand stimulated by the gramophone, radio, and movies. Experiments with electric pianos, guitars, and other amplified instruments in the 1920s and 1930s led to their commercial manufacture in the 1950s and 1960s and the creation of a distinctive pop and rock musical culture. Electroacoustic and computer-generated music, in which "sound objects" abstracted from their acoustic and notated sources could be manipulated in new ways, made their appearance. Pierre Schaeffer, who invented *musique concrète* in 1948, and Iannis Xenakis, whose stochastic compositions of the 1950s and 1960s were based on the applicability of the kinetic theory of gases to music, exemplify this genre of modern composition stimulated by new electronic and digital technologies.

Laboratories continued to be important sites for exploring and reconfiguring relationships between music and science throughout the late twentieth century, especially in the recording and telecommunications industries. In 1957, the first experiments in digital sound synthesis took place at the Bell Telephone Laboratories. They led not only to new musical applications but also to new research in the psychophysics of music. Since the 1960s advances in computer technologies and research into artificial intelligence have strongly dominated approaches to music analysis and music psychology, which in keeping with the increase in passive listening by mass audiences has concentrated more on studying responses to music than on analyzing the skills necessary for performance. The computational methods used by cognitive psychologists to investigate the processes of hearing, perception, and memory have also been complemented by neurophysiologists' studying music's effects on brain activity by means of PET (positron emission tomography) scans, which permit real-time observations of variations in blood flow across the brain. More recently, scientists have raised questions about a genetic basis for musical ability as the human genome project nears completion, but have found no definitive evidence.

The close relationship between Western science and Western music that persisted into the seventeenth century has continued. Yet once harmonic motion became expressible in a mathematical equation rather than vibrating strings, the importance of musical models for the natural and human sciences diminished. Although the string theory currently fascinating physicists resembles Hooke's concept of universal vibrating matter, modern cosmologists have not come to strings via music. And as the sciences become ever more specialized—acoustics itself being divided into numerous subdisciplines—the connection between music and any single science has fragmented. Nevertheless, some consistent patterns have emerged, especially the role of instruments in generating scientific knowledge about music. New instruments and techniques have been created to investigate the changes effected on human nature by music. These musical and scientific experiments have typically been linked through a shared reliance on mechanical, electrical, and, most recently, digital technologies.

Penelope Gouk